

# MARS INFRARED SPECTROSCOPY: FROM THEORY AND THE LABORATORY TO FIELD OBSERVATIONS

**June 4-6, 2002**  
**at the Lunar and Planetary Institute**

**Edited by**  
Laurel Kirkland, John Mustard, John McAfee, Bruce Hapke, Michael Ramsey

$$L(\lambda) = \tau \cdot B(\lambda, T) + L_U(\lambda) + [1 - \varepsilon(\lambda)] \cdot L_D(\lambda) \cdot \tau(\lambda)$$



## **Conveners:**

**Laurel Kirkland**  
Lunar and Planetary Institute and The Aerospace Corporation  
kirkland@lpi.usra.edu, 281-486-2112

**John Mustard**  
Brown University  
John\_Mustard@brown.edu

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Lunar and Planetary Institute, Houston



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*Schneebeil*: Quantification of Near-Infrared Photography of Snow Surfaces on Earth and Mars **[abs. 2002]**

*F. Seelos, R. Arvidson*: Mantled and Exhumed Terrains in Terra Meridiani **[abs. 2006]**

*G. Sellar, L. Kirkland, G. Boreman and D. Wang*, Novel Imaging Spectrometer With High Signal Collection Ability and No Moving Parts **[abs. 2011]**

### **MARS INFRARED SPECTROSCOPY: From Theory and the Laboratory to Field Observations**

The continuity and timely implementation of the Mars exploration strategy relies heavily on the ability of the planetary community to interpret infrared spectral data. However, the increasing mission rate, data volume, and data variety, combined with the small number of spectroscopists within the planetary community, will require a coordinated community effort for effective and timely interpretation of the newly acquired and planned data sets. Relevant spectroscopic instruments include the 1996 TES, 2001 THEMIS, 2003 Pancam, 2003 Mini-TES, 2003 Mars Express OMEGA, 2003 Mars Express PFS, and 2005 CRISM.

In light of that, leaders of the Mars spectral community met June 4–6 to address the question: What terrestrial theoretical, laboratory, and field studies are most needed to best support timely interpretations of current and planned visible/infrared spectrometer data sets, in light of the Mars Program goals?

A primary goal of the spectral community is to provide a reservoir of information to enhance and expand the exploration of Mars. Spectroscopy has a long history of providing the fundamental compositional discoveries in the solar system, from atmospheric constituents to surface mineralogy, from earth-based to spacecraft-based observations. However, such spectroscopic compositional discoveries, especially surface mineralogies, have usually come after long periods of detailed integration of remote observations, laboratory analyses, and field measurements. Spectroscopic information of surfaces is particularly complex and often is confounded by interference of broad, overlapping absorption features as well as confusing issues of mixtures, coatings, and grain size effects. Thus some spectroscopic compositional discoveries have come only after many years of research.

However, we are entering an era of Mars exploration with missions carrying sophisticated spectrometers launching about every 2 years. It is critical that each mission provide answers to relevant questions to optimize the success of the next mission. That will not occur effectively unless the spectroscopic remote sensing data can be processed and understood on an approximate 2-year rate. Our current knowledge of spectral properties of materials and confounding effects of the natural environment are not well enough understood for the accurate interpretations needed for such ambitious and time critical exploration objectives. This workshop focused on identifying critical gaps in moving the field towards the goal of rapid and accurate analysis and interpretation.

## RECOMMENDATIONS

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### SUMMARY

This report focuses on identification of critical gaps, particularly those that cannot be filled by individual researchers alone, and does not discuss the relative importance of ongoing research. The two most critical gaps are in coordinated end-to-end field testing and in libraries of spectroscopic data. Three related gaps are in data from terrestrial sites to aid TES and CRISM interpretations, lack of high quality development data to support landers, and delays in funding owing to lack of coordination between R&A proposal due dates and mission data releases.

### CRITICAL GAPS

1. End-to-end testing. Field/rover, airborne/satellite, and telescopic measurements are sensitive to very different effects, and these differ from those present in the laboratory. Thus a convincing determination of uncertainties as related to studies of Mars requires demonstration through coordinated “end-to-end” field testing. This should proceed in light of our current best understanding of martian mineralogy and environment, using:

- (1) Data sets of appropriate terrestrial analog sites that are measured with both geometric and spectral fidelity as close as possible to landed and orbital flight instruments;
- (2) Interpretation using spectral libraries and theoretical work as applied to data of Mars;
- (3) Reporting interpretations at a community workshop, including a “blind test” (with minimal foreknowledge of the test site or ground truth);
- (4) Validation through ground truth.

This will:

- (1) Test mission protocols and interpretation methods used for flight data;
- (2) Develop theoretical ties and address critical current uncertainties in detectability, uniqueness of identifications, abundance mapping, and atmospheric compensations;
- (3) Prepare the community to interpret flight data in a timely manner;
- (4) Help define and highlight gaps in public spectral libraries, and the importance of the libraries and theoretical work to the interpretation chain.

Coordination through an independent steering group is critical in order to maintain and facilitate a clear focus on addressing the central questions. This is imperative to support timely interpretations and to plan and manage future flight instruments, but it cannot be achieved by individual researchers alone. Further, in order to achieve results in time to support the current suite of missions, this program needs to begin as soon as possible with adequate and focused funding.

2. Public libraries of spectroscopic data. Interpretation quality is limited to the quality of the accessible spectral libraries. Current public libraries focus on specific issues or conditions (such as major groups of igneous minerals and terrestrial weathering products, and large particles). Primary gaps include (1) systematic measurements of other weathering products, coatings, a range of surface textures, full particle size ranges; (2) measurements made under simulated Martian conditions; (3) motivating and facilitating a conversion of private libraries into the public domain; and (4) systematic development of fundamental optical constants for modeling. Currently there is insufficient funding and staffing to measure, document and prepare for public release documented digital spectral libraries. It is unclear which R&A program is responsible for developing strong public libraries, and this should be clarified in the appropriate Announcement of Opportunity. Additions and public access should be fostered in cooperation with NASA’s Planetary Data System.

### ADDITIONAL GAPS

3. High fidelity data. There are gaps in terrestrial hyperspectral airborne/satellite data sets for CRISM and OMEGA (mainly 2.5–5  $\mu\text{m}$ ), and essentially no thermal-IR hyperspectral airborne or satellite data sets comparable to TES exist in the NASA community. Data should be identified and made publicly available to allow validation of methods, interpretations, and uncertainties.

4. Lander development data. The NASA community has essentially no field data sets available measured with high fidelity to the lander Mini-TES or Pancam or similar to future landers. Data should be identified and made available to allow development and validation of methods, and to expedite community contributions after the flight data sets are released.

5. Mismatch of flight data release and R&A cycle timing delays community research. When the first public release of flight data occurs after the relevant Research and Analysis (R&A) program deadlines, it can delay funding non-team member research ~2 years from initial data return. For example, this delay will occur for Odyssey research. This is a significant weakness given the rapid turnover rate of current missions. R&A management should coordinate with flight teams and the PDS to officially release demonstration flight data timed to prevent this additional delay.

Participants of the workshop,

#### *Mars Infrared Spectroscopy: From Theory and the Laboratory to Field Observations*

Raymond Arvidson	Donald Barker	Janice Bishop	Diana Blaney
Don Burt	John Cipar	Roger Clark	Kim Deal
Sergio Fonti	Bruce Hapke	Laurel Kirkland	John McAfee
Daniel McCleese	Richard Morris	Scott Murchie	John Mustard
Carlé Pieters	Michael Ramsey	Steve Saunders	Bernard Schmitt
Frank Seelos	R. Glenn Sellar	Maria Sgavetti	Ann Sprague
Shawn Wright			

## **Spectroscopic Data for Mars**

The missions associated with the Mars Exploration Program (MEP) as well as missions from other countries and international agencies, will acquire abundant spectroscopic observations to determine surface composition. Below is a short summary of the existing and expected data sets:

### **1) Defined Spectroscopic Instruments**

- Continued analysis and interpretation of TES/MGS data and THEMIS/Odyssey
- New data from Pancam and Mini-TES on the MER rovers (2004)
- New data from PFS and OMEGA on Mars Express (2004–2007)
- New data from CRISM on MRO (2006–2009)

### **2) Planning for 2007–2020**

- Possible instruments proposed for Scout mission (2007)
- Planned NASA contribution to CNES orbiter (2007)
- Instruments on the Mars Smart Lander (MSL) (2009)
- Beyond MSL are possible additional Scout missions, landers, and Sample Return

### **3) How will IR Spectroscopy contribute in the next decade**

- Data analysis and interpretation of orbital assets
- Data analysis and interpretation of landed assets
- Integration of orbital and lander data for sample return targeting, investigation of planet

## Specific Gaps and Recommendations

### 1. Terrestrial analog testing of the complete theory-lab-field-airborne/satellite chain.

The steering group's critical role is to facilitate and maintain a strong focus on addressing the central questions outlined in the summary. The steering group should:

- (1) Facilitate and collect community input.
- (2) Select appropriate terrestrial field sites.
- (3) Facilitate making appropriate data publicly available. This may draw on data sets measured for other studies.
- (4) Facilitate reporting at a community workshop, including discussion of what the results indicate for meshing current and future measurements with the Mars exploration program.

End-to-end spectroscopy research of terrestrial analog sites that includes field/rover, airborne/satellite, laboratory work, and theory is important. The specific implementation could take several forms but must be designed to address fundamental problems in field/rover, airborne/satellite, telescopic, and theoretical work as applied to interpretations of data sets of Mars. Interlinking of the perspectives through theoretical work is also important. However, it is not sufficient to collect and release the data; analysis must be funded. In addition, collaboration between the Space Science enterprises and terrestrial communities in spectroscopy should be encouraged and facilitated.

### 2a. Community spectral libraries.

*Data gaps:* There is an insufficient range of weathering products, coatings, textures, small particle size ranges ( $<50\text{--}100\text{ }\mu\text{m}$ ), pure as well as mixed materials (composition and size distribution), transmission, optical constants, packing effects, and measurements at low temperature and in low pressure  $\text{CO}_2$  using well-characterized samples.

*Well-characterized* includes (1) location or origin of sample; (2) chemical characterization, including major element analyses, solution pH and electrical conductivity, thermal and evolved gas analyses (e.g., differential scanning calorimetry (DSC) integrated with a mass spectrometer); (3) mineralogical characterization, including from Moessbauer and Raman spectroscopy, magnetic properties (magnetic susceptibility and saturation magnetization), powder X-ray diffraction, petrographic analyses of thin sections; (4) physical characterization, including bulk density, porosity, fabric, surface texture, and particle size distribution analysis. Chemical and mineralogical characterization can be done for each size separate, and magnetic separate analysis for soils. Chemical and mineralogical characterization can be done for each magnetic separate. However, not all these need be done on each sample. Sample characterization is the most time consuming step: it is estimated that it takes 2 to 3 weeks per sample to provide all the verification listed here.

*Production gap:* Researchers typically measure spectra to examine a particular question, not to create a public data base. Although it is highly desired to make data publicly accessible, the motivation for researchers to spend unfunded time to do so is unclear, particularly when the spectra were measured through unfunded or non-NASA funded means.

*Distribution gap:* No central location coordinates linking to the available public libraries, and no guidelines exist for individuals the archive their own data on-line.

*Recommendation:* The PDS Geoscience Node should maintain a web page with links to the currently available libraries of spectroscopic data and solicit or create links for additional data sites. PDS should provide guidelines and options for organizing (along with appropriate supplemental information/comments), posting, and referencing spectral libraries acquired or assembled under the R&A program. For continuity, PDS should also maintain a mirror site and back-up capabilities.



*R&A gap:* It is unclear which R&A program is responsible for funding spectral library development specifically intended for public access.

*Recommendation:* The appropriate R&A program associated with the Mars program (e.g. MDAP) should state in the AO an interest in funding VIS/IR public spectral libraries to support interpretation of current and planned data sets, and specifically include public production both of data already measured and to be measured. This will clarify where and what to propose. Additionally, PI's funded to produce public spectral libraries should have that funding continued only when they make the spectroscopic data public on schedule as proposed.

*Theoretical studies and links with spectral libraries:* The surface and atmosphere of Mars very probably contain an abundance of micrometer-sized particles, which are much smaller than the wavelengths used in thermal remote sensing. The small size regime is poorly understood for two reasons: (1) Coherent interactions between particles are important. (2) Weak bands are strongly displayed in the spectra of small particles; however, the spectra in some libraries were made using large particles, in which weak bands are poorly displayed.

*Recommendations:* Extend spectral libraries to include media of micrometer-sized particles, including mixed media with a range of size distributions. Publishing complex refractive indices would be extremely valuable, provided that measurement methods, such as transmission are used that are sensitive to weak as well as strong bands. Laboratory spectral measurements designed to study coherent effects (e.g. intimate mixtures, packing effects) are also needed.

**2b. Laboratory instrumentation.** There are important gaps in attachments and environmental chambers for laboratory instrumentation:

*Facility gap:* Hemispherical reflectance measurements may be necessary in the thermal-infrared for small particle size ranges, because they typically have a temperature gradient that causes spectral artifacts when measured in emission. However, a gap in hemispherical reflectance capabilities exists from 25–50  $\mu\text{m}$ .

*Facility gap:* Insufficient environmental capabilities exist to mimic the low pressure, desiccating, and cold (<150 K) conditions on Mars, and at high temperature to drive off bound water (>380 K).

*Funding gap:* Ensure sustained funding to upgrade current equipment

**3a. TIR airborne/satellite data.** There are essentially no publicly available airborne/satellite TIR hyperspectral data sets. Hyperspectral data are required to address uniqueness, quantification, and detectability questions for satellite and airborne hyperspectral studies of Mars.

*Data gap:* Hyperspectral TIR data are largely in the DoD community. Desired data include surface measurements and upward emission function (emission phase function, EPF) data.

*Recommendation:* The planetary community should make its needs known to communities who have hyperspectral TIR data. Hyperspectral data sets may be available if asked for.

*Options:* Options to allow validation of hyperspectral methods include:

- A. Develop and purchase a community spectrometer
- B. Sponsor a group that has the instrumentation to measure data and make it publicly available (full NASA funding)
- C. Propose joint measurements with a group that has the instrumentation (shared funding)
- D. Request piggyback measurements on other work performed by a group that has the instrumentation (no NASA funding provided, making availability unpredictable)

- E. Interpret Mars hyperspectral data sets without benefit of similar terrestrial hyperspectral experience validated by ground truth.

*Research gaps:*

- A. Uniqueness of mineral identification when ground truth is not available
- B. There is no terrestrial hyperspectral study that validates the main atmospheric compensation technique used for TES data
- C. Testing and validation of current quantitative abundance mapping methods using terrestrial hyperspectral data validated by ground truth.

**3b. VIS/NIR airborne or satellite instrumentation.**

*Data gaps:* The  $\sim 2.5\text{--}5\text{ }\mu\text{m}$  range has both reflected and emitted light, which requires development and testing of techniques for interpretation to support CRISM. No data in the NASA community covering this range was identified, but other communities have instrumentation that covers this range.

*Data gaps for atmospheric compensation studies:* CRISM plans to compensate for atmospheric interference using upward emission function (emission phase functions, EPF), but no public data sets exist to study this technique over the  $1\text{--}5\text{ }\mu\text{m}$  range. However, it was unclear how important this gap is, since coverage of shorter and longer wavelength regions is available that could be used to develop and test techniques.

**3c. Ground-based telescopic spectroscopy:** Measuring atmospheric constituents like ozone and water vapor, and clouds and circulation have an important role in the Mars program. Ground-based measurements provide global coverage and long term systematic baseline measurements that the current Mars flight program is not designed to provide.

**4a. TIR field spectrometers.**

*Data gap:* Almost no NASA research exists using data measured with high fidelity to the 2003 lander spectrometer. Nearly all NASA data sets are measured looking straight down at the surface, while lander spectrometers will measure more horizontally and over a wide range of angles.

*Facility gap (high fidelity):* Options to allow high fidelity testing and to prepare the community include:

- A. Develop and purchase a community TIR imaging field spectrometer
- B. Sponsor a group that has the instrumentation to measure data and make it publicly available (full NASA funding)
- C. Propose joint measurements with a group that has the instrumentation (shared funding)
- D. Request piggyback measurements on other work performed by a group that has the instrumentation (no NASA funding provided, making availability unpredictable)
- E. Interpret Mars data sets without benefit of similar terrestrial experience validated by ground truth.

*Facility gap (low-fidelity):* Three groups can make point (non-imaging) measurements, with one instrument shared among three universities, so five research groups have access to a non-imaging instrument. Although these are low fidelity to the flight instruments, they are important for research and teaching.

*Recommendation:* Modest investment in a point-measuring spectrometer is warranted, if the instrument is managed in a manner to make it openly available to the community.

#### **4b. VIS/NIR field spectrometers.**

*Facility gap:* No facility to cover the 2.5–5  $\mu\text{m}$  range was identified in the NASA community.

*Data gap:* Too little research has occurred using data measured in a geometry similar to landers. Most data sets are measured looking straight down at the surface, while lander spectrometers will view the scene more horizontally and over a wide range of angles. No field data covering the 2.5–5  $\mu\text{m}$  range was identified in the NASA community.

#### **5. Mesh first community access to flight data with the R&A cycle.**

*Gap:* The period where only the instrument team has access to Odyssey data ends in October 2002, after the deadline for Mars-related R&A programs has passed (e.g. MDAP is due in Aug). Thus non-team members must wait until the following year's R&A to propose on even footing (~Aug 2003); followed by at least a ~6 month delay in funding (~Feb 2004). The total can delay R&A funded non-team member research by at least ~2 years from initial Odyssey data return (Feb 2002). This is a significant delay in light of the 26 month Mars mission cycle, and it reduces the community's engagement and capacity to address gaps in research that would aid the Mars program goals.

*Recommendation:* Officially release sufficient demonstration data and documentation in time to support proposals on an even footing. This requires coordination between R&A management, instrument teams, and the PDS to define:

- A. When the data have to be available to mesh with the most relevant R&A program deadline(s)
- B. The volume/type of preliminary data (e.g. how many images?).
- C. Completeness (e.g. are full band THEMIS data needed?).
- D. Who would release the data (PDS or PI).
- E. How to announce it is available (e.g. through the R&A program).

## PROGRAM

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**TUESDAY, June 4, 2002**

Doors open at 7:45. Posters can be put up, and we will have a table for reprints and handouts.

**7:45–8:15 Registration (\$15)**

**8:25 Welcome**

\* = speaker

### **8:30 Mars Program: Current and Future Goals**

**Chair: Bishop**

8:30–8:55 \*S. Saunders: Science Involvement in Mars Exploration in the First Decade of the Twenty-First Century

8:55–9:20 \*D. McCleese: Future Robotic Exploration of Mars: 2005–2020

9:20–9:45 \*R. Arvidson: Mars Exploration and Importance of Spectroscopic Observations

### **9:45 Discussion: Program Goals and Spectral Observations**

**Moderator: Bishop**

How do spectral observations fit into the Mars program?

**10:15–10:35 Break**

### **10:35 Current and Planned Data Sets of Mars' Surface**

**Chair: Pieters**

10:35–11:00 telescopic: \*A. Sprague

11:00–11:20 ISM: \*J. Mustard: Review of the ISM Instrument and Results

11:20–11:50 TES: \*F. Seelos, R. Arvidson: Mantled and Exhumed Terrains in Terra Meridiani

### **11:50–1:15 Lunch**

1:15–1:55 TES: \*R. Clark: Spectral Feature Mapping and Analysis of Mars Global Surveyor Thermal Emission Spectrometer Data

1:55–2:20 THEMIS: \*S. Saunders

2:20–2:40 Mini-TES

### **2:40–3:00 Break**

3:00–3:20 Pancam: \*D. Morris

3:20–3:45 Mars Express OMEGA: \*B. Schmidt, Douté, Erard, Langevin: Discrimination Between Solid, Liquid and Gaseous H<sub>2</sub>O, and Assessment of H<sub>2</sub>O Temperature by Spectroscopy Using the OMEGA Imaging Spectrometer

3:45–4:05 Mars Express PFS: V. Formisano, \*S. Fonti et al.: The Planetary Fourier Spectrometer (PFS) Onboard the European Mars Express Mission

4:05–4:25 CRISM: \*S. Murchie et al.: CRISM: Compact Reconnaissance Imaging Spectrometer for Mars on the Mars Reconnaissance Orbiter

### **4:30–5:00 Discussion: How to mesh instrument data release with the R&A cycle**

**Moderator: Saunders**

### **5:00–6:00 Reception and Posters**

Beer and Light Refreshments Served

## WEDNESDAY Morning, June 5

*Doors open at 7:45*

### 8:15 Theory and Laboratory

**Chair: Murchie**

8:15–8:55 \*B. Hapke: Status of Reflectance and Emissivity Models Relevant to Mars Studies

8:55–9:20 \*R. Morris: Martian Analogue Sample Characterization and Spectral Library Development at the Johnson Space Center

9:20–9:45 \*S. Fonti et al.: A Coordinated Laboratory Program in Support of the Spectroscopic Experiments on Board Martian Missions

### 9:45–10:05 Break

10:05–10:30 \*C. Pieters: Mid-Infrared Reflectance Spectroscopy: Where Are We, Where Are We Going, and Why?

10:30–10:55 \*J. Mustard: Methods of Spectral Analysis

### 10:55–12:10 Break-Out Groups: Theory and Laboratory through lunch (brought in at 11:30)

\* = present results in the panel discussion

*All questions are open to all groups, but each group should address their question(s) in-depth first.*

**Group 1:** Granahan, Murchie, \*Pieters, Saunders, Schneebeli, Sprague

VIS/NIR theoretical and lab studies: What are the critical gaps, and what studies are most needed to address those gaps?

**Group 2:** Bishop, \*Fonti, McCleese, Ramsey, Hapke, Wright

Thermal-IR theoretical and lab studies: What are the critical gaps, and what studies are most needed to address those gaps?

**Group 3:** Arvidson, Barker, Deal, Kirkland, \*Morris, Sellar

What community spectral libraries are most needed?

What lab instrumentation is available?

What lab instrumentation is most needed?

**Group 4:** Blaney, Cipar, \*Clark, Mustard, Schmidt, McAfee, Seelos

Getting lab data to the community:

Who should deliver it (e.g. PI, PDS...)?

Who should fund distribution (e.g. R&A, PDS...)?

Who should define what is needed (samples, wavelength range, reflectance vs. emission,...)

How does and should the community have input?

### 12:10–1:10 Theory and Laboratory Panel Discussion

**Moderator: Sprague**

## WEDNESDAY Afternoon, June 5

### 1:10 Field and Airborne

Chair: Clark

1:10–1:35 field-rover VIS/NIR: \*D. Blaney: Visible To Short Wavelength Infrared Spectroscopy On Rovers: Why We Need It On Mars and What We Need To Do On Earth

1:35–2:00 field-rover thermal: \*J. McAfee, L. Kirkland: Thermal Infrared Field Spectroscopy

#### 2:00–2:20 Break

2:20–2:45 airborne VIS/NIR: E. Guinness, \*R. Arvidson, B. Jolliff, R. Morris, D. Ming: Mapping Lithologic Units Exposed on The Summit of Mauna Kea Using AVIRIS Hyperspectral Reflectance Data

2:45–3:10 combined: \*J. Bishop, M. Lane, E. Murad: The Power of Combining Multiple Spectroscopic Techniques for Mineral Identification on Mars and the Necessity of Lab and Field Study of Analog Materials

3:10–3:35 airborne/satellite thermal: \*M. Ramsey: Using Terrestrial Multispectral Images as a Proxy for Constraining New Thermal Infrared Data of Mars

3:35–4:00 \*Schneebeil: Quantification of Near-Infrared Photography of Snow Surfaces on Earth and Mars

#### 4:00–4:15 Break

### 4:15–5:15 Break-Out Groups: Field and Airborne

\* = present results in the panel discussion

*All questions are open to all groups, but each group should address their question(s) first.*

**Group 1:** Arvidson, Hapke, Mustard, \*Ramsey, Fonti, Sellar, Wright

Thermal-IR field/airborne studies: What are the critical gaps, and what studies are most needed?

Thermal-IR current capabilities: What field and airborne data sets should be measured specifically for release to the community using current instruments? Who should define what to measure (field sites, wavelength range, multi-vs. hyperspectral, imaging vs. point measurements,...)? How does and should the community have input? Who should deliver it (e.g. PI, PDS...)? Who should fund distribution (e.g. R&A, PDS...)?

**Group 2:** \*Blaney, Cipar, Kirkland, McAfee, McCleese, Seelos

Thermal-IR field/airborne studies: What are the critical gaps, and what studies are most needed?

Thermal-IR field/airborne future capabilities: What additional instrumentation is most needed (if any)?

**Group 3:** Barker, Bishop, Clark, McAfee, Morris, \*Murchie, Schmidt

VIS/NIR field/airborne studies: What are the critical gaps, and what studies are most needed?

VIS/NIR current capabilities: What field and airborne data sets should be measured specifically for release to the community using current instruments? Who should define what to measure (field sites, wavelength range, multi-vs. hyperspectral, imaging vs. point measurements,...)? How does and should the community have input? Who should deliver it (e.g. PI, PDS...)? Who should fund distribution (e.g. R&A, PDS...)?

**Group 4:** Deal, \*Granahan, Pieters, Saunders, Schneebeil, Sprague

VIS/NIR field/airborne studies: What are the critical gaps, and what studies are most needed?

VIS/NIR field/airborne future capabilities: What additional instrumentation is most needed (if any)?

### 6:00 Group dinner (Italian Cafe)

**THURSDAY, June 6**

*Doors open at 7:45*

**8:15–9:30 Field and Airborne Panel**

**Moderator: Mustard**

**9:30–9:50 Break**

**9:50–10:50 Break-Out Groups: Final Report**

\* = present results in the panel discussion

*All questions are open to all groups, but each group should address their question(s) in-depth first.*

**Group 1:** Barker, Bishop, Clark, Fonti, Ramsey, \*Saunders

What studies are most needed to attain the critical goals of the Mars Program to support searching for possible mineral biomarkers and environments that could preserve signatures of life?

**Group 2:** Deal, \*Hapke, Morris, Murchie, Schneebeil, Sprague

What studies are most needed to attain the critical goals of the Mars Program to support interpretations for answering basic questions in geology and volatile budget?

**Group 3:** Blaney, Granahan, \*McCleese, Mustard, Schmidt, Wright

Contingency plans: If a currently slated spectral data set is not returned or is not as productive as planned, would requirements or priorities for supporting studies change?

**Group 4:** \*Arvidson, Cipar, Kirkland, McAfee, Pieters, Seelos, Sellar

What lab, field, airborne instrumentation is most needed?

What community spectral libraries are most needed?

What field and airborne data sets should be measured specifically for release to the community?

How to get data to the community?

How to mesh data release with the R&A cycle?

**10:50–12:10 Panel discussion for the report**

**Moderator: Kirkland**

## PARTICIPANTS

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### **Raymond Arvidson**

Washington University St. Louis  
1 Brookings Drive, Campus Box 1169  
St. Louis, MO 63130  
Phone: 314-935-5609  
Fax: 314-935-4998  
email: arvidson@wunder.wustl.edu

### **Donald Barker**

NASA Johnson Space Center  
MOD, Mail Stop DF 64  
Houston, TX 77058  
Phone: 281-483-9501  
email: donald.c.barker@jsc.nasa.gov

### **Janice Bishop**

NASA Ames Research Center  
SETI Institute  
Mail Stop 239-4  
Moffett Field, CA 94035  
Phone: 650-604-0297  
Fax: 650-604-1088  
email: jbishop@mail.arc.nasa.gov

### **Diana Blaney**

Jet Propulsion Laboratory  
Mail Stop 183-501  
4800 Oak Grove Drive  
Pasadena, CA 91109  
Phone: 818-354-5319  
Fax: 818-354-0966  
email: diana.l.blaney@jpl.nasa.gov

### **Don Burt**

Arizona State University  
Mail Code 1404  
Tempe, AZ 85287  
Phone: 480-965-6180  
email: DONALD.BURT@asu.edu

### **John Cipar**

Air Force Research Laboratory  
29 Randolph Rd.  
Hanscom AFB, MA 01731  
Phone: 781-377-3767  
email: john.cipar@hanscom.af.mil

### **Roger Clark**

USGS, Denver  
Mail Stop 5964  
Box 25046  
Denver, CO 80225  
Phone: 303-236-1332  
email: rclark@speclab.cr.usgs.gov

### **Kim Deal**

Washington University  
Campus Box 1169  
1 Brookings Drive  
St. Louis, MO 63130  
email: deal@levee.wustl.edu

### **Sergio Fonti**

University of Lecce  
Physics Department  
C.P. 193 - Via Arnesano  
Lecce, 73100, Italy  
Phone: 39-0832-320493  
email: sergio.fonti@le.infn.it

### **Bruce Hapke**

University of Pittsburgh  
200 SRCC Bldg.  
4107 O'Hara St.  
Pittsburgh, PA 15260  
Phone: 412-624-8876  
email: hapke@pitt.edu

### **Laurel Kirkland**

Lunar and Planetary Institute  
3600 Bay Area Blvd.  
Houston, TX 77058-1113  
Phone: 281-486-2112  
email: kirkland@lpi.usra.edu



**John McAfee**

Deputy Division Leader DX  
DX-DO, MS P918  
Los Alamos National Laboratory  
Los Alamos, NM 87545  
Phone: 505-667-6874  
email: mcphi@lanl.gov

**Daniel McCleese**

Jet Propulsion Lab  
Mail Stop 264-426  
4800 Oak Grove Drive  
Pasadena, CA 91109  
Phone: 818-354-2317  
email: daniel.j.mccleese@jpl.nasa.gov

**Richard Morris**

NASA Johnson Space Center  
Mail Stop SR  
Houston, TX 77058  
Phone: 281-483-5040  
email: richard.v.morris1@jsc.nasa.gov

**Scott Murchie**

Johns Hopkins University-Applied Physics  
Lab  
Room 4-112  
11100 Johns Hopkins Road  
Laurel, MD 20723  
Phone: 240-228-6235  
email: murchie@jhuapl.edu

**John Mustard**

Brown University  
Geological Sciences  
Box 1846  
Providence, RI 02912  
Phone: 401-863-2417  
email: John\_Mustard@brown.edu

**Carlé Pieters**

Brown University  
Geological Sciences  
Box 1846  
Providence, RI 02912  
Phone: 401-863-2417  
email: Carle\_Pieters@Brown.EDU

**Michael Ramsey**

University of Pittsburgh  
Department of Geology and Planetary Science  
Pittsburgh, PA 15260-3332  
email: ramsey@ivis.eps.pitt.edu

**Steve Saunders**

Jet Propulsion Lab  
Mail Stop 180-701  
4800 Oak Grove Drive  
Pasadena, CA 91109  
Phone: 818-354-2867  
email: saunders@scn1.jpl.nasa.gov

**Bernard Schmitt**

Centre Nationale de la Recherche Scientifique  
Laboratoire de Planetologie de Grenoble  
BP 53, France

**Frank Seelos**

Washington University  
Campus Box 1169  
1 Brookings Drive  
St. Louis, MO 63130  
Phone: 314-935-8594  
email: seelos@levee.wustl.edu

**R. Glenn Sellar**

Florida Space Institute  
12424 Research Parkway, Suite 400  
Orlando, FL 32826  
Phone: 407-659-5597  
email: gsellar@mail.ucf.edu

**Maria Sgavetti**

email: maria.sgavetti@ipruniv.cce.unipr.it

**Ann Sprague**

University of Arizona

Lunar and Planetary Lab

1629 E. University Blvd.

Tucson, AZ 85721-0092

Phone: 520-621-2282

email: sprague@LPL.Arizona.EDU

**Shawn Wright**

University of Pittsburgh

Department of Geology and Planetary Science

Pittsburgh, PA 15260-3332

email: ShawnWright@pittsburghpanthers.com



**MARS EXPLORATION AND IMPORTANCE OF SPECTROSCOPIC OBSERVATIONS.** R. E. Arvidson, Department of Earth and Planetary Sciences, McDonnell Center for the Space Sciences, Washington University, St. Louis, Missouri, 63130; arvidson@wunder.wustl.edu

An update will be given based on the work by the Pathways Science Steering Subgroup of the Mars Exploration Payload Analysis Group (MEPAG), focusing on planned and needed spectroscopic investigations from orbit and from the surface that would pursue science objectives associated with climate, life, resources, and the role of water. This Subgroup is chartered to examine the mission set and expected results through the 2009 Mars Smart Lander (MSL) Mission and to postulate alternate discovery-driven investigation pathways that

NASA might take in exploring Mars during the next decade. An emphasis will be on global understanding of the tectonic and climatic cycles and whether or not they conspired to produce suitable habitats for life of Mars. Summaries will be provided for observation capabilities associated with existing and planned spectroscopic systems through MSL and requirements derived and presented for several investigation-driven pathways for the next decade.

Mars Infrared Spectroscopy: From Theory and the Laboratory to Field Observations, June 4-6, 2002, Lunar and Planetary Institute, Houston, TX.

## The Power of Combining Multiple Spectroscopic Techniques for Mineral Identification on Mars and the Necessity of Lab and Field Study of Analog Materials.

J. L. Bishop<sup>1</sup>, M. D. Lane<sup>2</sup>, and E. Murad<sup>3</sup>, <sup>1</sup>SETI Institute/NASA-ARC, MS-239-4, Moffett Field, CA 94035 (jbishop@mail.arc.nasa.gov), <sup>2</sup>Planetary Science Institute, 620 N. 6th Ave., Tucson, AZ, 85705, <sup>3</sup>Bavarian Geol. Survey, Leopoldstrasse 30, Postfach 389, D-95603 Marktredwitz, Germany.

**Introduction:** Martian surface composition analysis should include multiple types of spectral measurements in order to maximize the information to be gained. Mars research is utilizing this concept in combining thermal IR (TES and THEMIS) with visible/NIR (Omega and CRISM) global spectral measurements in current and upcoming missions, as well as a combination of multispectral visible/NIR and hyperspectral thermal IR on the 2003 MERs. What we need urgently to support these missions are studies of analog materials, both in the lab and *in situ*. These studies should include hyperspectral visible/NIR, mid-IR and Raman data in order to be applicable to future missions where these data will hopefully be collected on Mars.

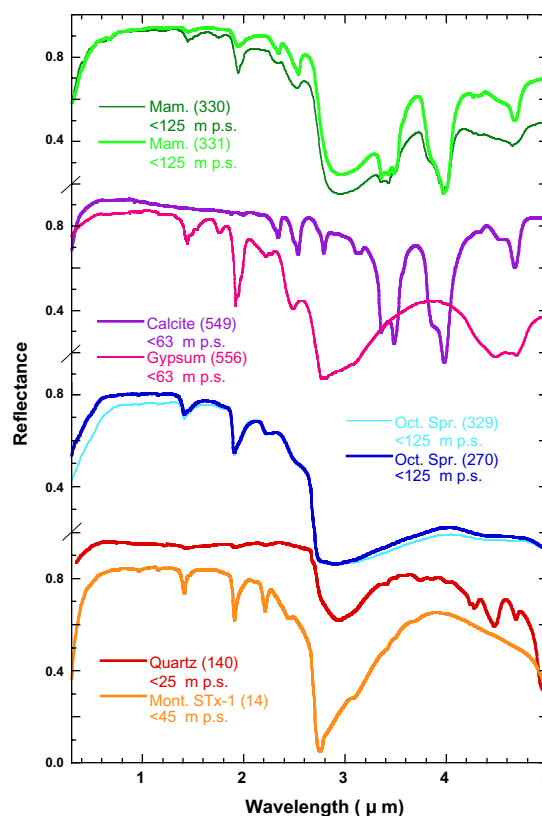
**Current Study:** Results are summarized here for a spectral study of two hydrothermal rocks from Yellowstone. Many of the minerals present in hydrothermal samples may be associated with organisms and may be useful as indicators of life or environments supportive of life on Mars. Spectra so far on this project have been performed in the laboratory on rock samples and powders. Samples such as these need to be studied *in situ* in the field as well in order to address a broader range of measurement concerns.

Preliminary work on this project was reported at the 2001 Mars technology workshop [1]. The samples were provided by Rocco Mancinelli. X-ray diffraction of the silicate rock indicates the presence of a combination of silicate species including opal-A and cristobalite, as well as poorly crystalline phases of tridymite or other SiO<sub>4</sub> polymorphs.

**Visible/NIR Spectra:** Two visible/NIR spectra are shown in Figure 1 of <125  $\mu\text{m}$  powders of a hydrothermal rock collected at the Mammoth Formation. One spectrum (331) is dominated by calcite spectral bands and the other contains spectral features characteristic of both calcite and gypsum. Spectra of these minerals are shown for comparison. The calcite and gypsum samples are described in a previous study [2].

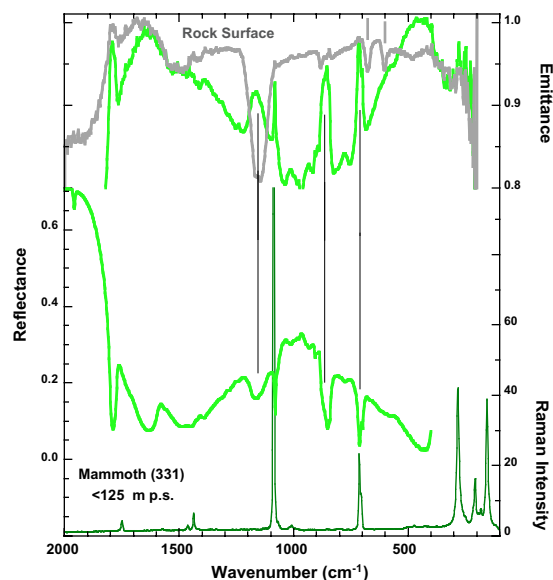
Two visible/NIR spectra are shown in Figure 1 of <125  $\mu\text{m}$  powders of a hydrothermal rock collected at Octopus Springs. The spectral bands near 1.41, 1.9 and 2.2  $\mu\text{m}$  are consistent with the presence of montmorillonite, but could also be due to some other Al-OH species. The weak bands near 1.37 and 2.22  $\mu\text{m}$  are attributed to Si-OH species based on work by

[3]. Spectra of montmorillonite [4] and quartz [5] are shown for comparison. The finely ground quartz sample contains features near 1.4 and 2.2  $\mu\text{m}$  attributed to Si-OH groups formed on the surface through grinding, and near 1.9 and 2.9  $\mu\text{m}$  attributed to H<sub>2</sub>O adsorbed on the surface.

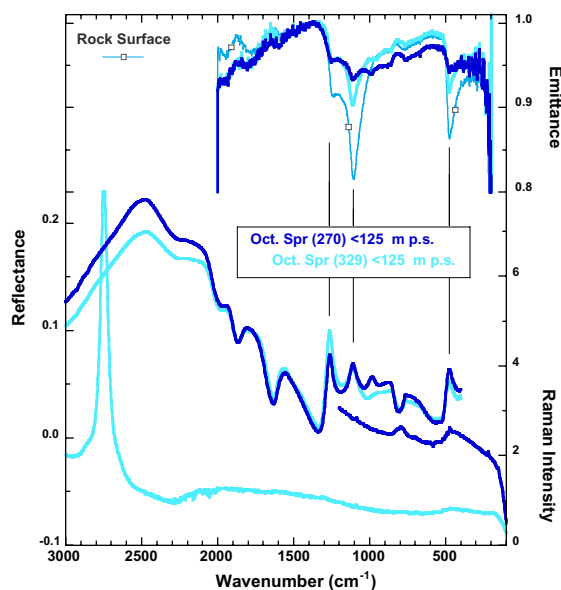


**Figure 1.** Visible/NIR reflectance spectra of a carbonate rock from Mammoth Formation and a silicate rock from Octopus Springs, Yellowstone.

**Mid-IR & Raman Spectra:** Emission, reflectance and Raman spectra are shown in Figure 2 of the same particulate sample (331) of the Mammoth Formation rock. These spectra all exhibit features characteristic of calcite. In addition, an emission spectrum is shown of the rock surface that exhibits spectral bands due to calcite and gypsum. Black lines are shown near 1150, 870 and 710  $\text{cm}^{-1}$  where strong calcite IR bands are observed. Strong Raman bands due to calcite are observed at 1085, 712, 285 and 158  $\text{cm}^{-1}$ . Gray lines are shown near 680 and 600  $\text{cm}^{-1}$  where characteristic gypsum bands are present.



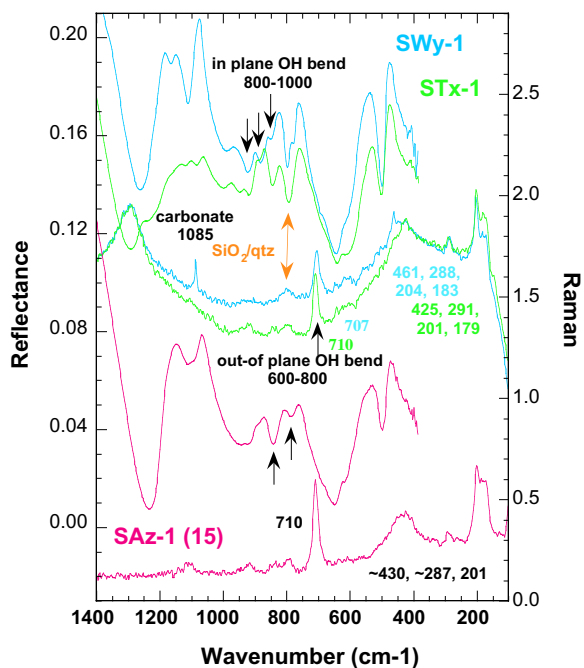
**Figure 2.** Mid-IR reflectance, emission, and Raman spectra of a carbonate rock from Mammoth Formation, Yellowstone.



**Figure 3.** Mid-IR reflectance, emission, and Raman spectra of a silicate rock from Octopus Springs, Yellowstone.

Emission, reflectance and Raman spectra are shown in Figure 3 of two particulate samples (270, 329) of the Octopus Springs rock. Black lines are shown near 1270, 1100 and 500  $\text{cm}^{-1}$  where silicate bands are observed in the IR spectra. The restrahlen band near 1270  $\text{cm}^{-1}$  is attributed to  $\text{SiO}_2$ , while the restrahlen bands near 1100 and 500  $\text{cm}^{-1}$  are attributed to  $\text{SiO}_4$ . An absorption band near 800  $\text{cm}^{-1}$  is attributed to Si-OH bending. Two Raman spectra are shown as well.

The strongest Raman band is present near 2800  $\text{cm}^{-1}$  for sample 329 and is characteristic of CH stretching vibrations [6]. The Raman spectrum for sample 270 contains weak bands near 800 and 430-470  $\text{cm}^{-1}$  that are attributed to Si-OH bending at 800  $\text{cm}^{-1}$ , and bending in distorted  $\text{SiO}_4$  groups near 470  $\text{cm}^{-1}$ , e.g. [7]. Raman bands are observed near 710, 430 and 200  $\text{cm}^{-1}$  in montmorillonite (Figure 4 and [7, 8]) and may explain weaker bands and shoulders at these positions.



**Figure 4.** Mid-IR reflectance and Raman spectra of three montmorillonite samples from the Clay Minerals Society. All are dry sieved to  $<45 \mu\text{m}$  and contain carbonate, silica and/or quartz impurities. The STx-1 and SWy-1 reflectance spectra are offset by +0.1 for clarity.

**Summary:** Spectroscopic studies of Mars analog materials need to be pursued that combine multiple spectral ranges and techniques in order to gain the ground truth necessary for interpretation of rocks and soils on Mars. These studies need to be performed on samples in the lab and in the field.

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**VISIBLE TO SHORT WAVELENGTH INFRARED SPECTROSCOPY ON ROVERS: WHY WE NEED IT ON MARS AND WHAT WE NEED TO DO ON EARTH.** D. L. Blaney, Jet Propulsion Laboratory, 4800 Oak Grove Dr., MS183-501, Email: Diana.Blaney@jpl.nasa.gov

**Introduction:** The next stage of Mars exploration will include the use of rovers to seek out specific mineralogies. Understanding the mineralogical diversity of the locale will be used to determine which targets should be investigated with the full suite of in situ capability on the rover. Visible to Short Wavelength Infrared (VSWIR) spectroscopy is critical in evaluating the mineralogical diversity and to validate the global remote sensing data sets to be collected by Mars Express and the Mars Reconnaissance Orbiter. However, spectroscopy on mobile platforms present challenges in both the design of instruments and in the efficient operation of the instrument and mission. Field-testing and validation on Earth can be used to develop instrument requirements analysis tools needed for use on Mars.

**VSWIR Spectroscopy:** To fully address the evolution of the Martian surface, the mineralogy and geologic context of both the original igneous material and the alteration products must be determined. Many unanswered questions remain about how the fresh igneous material on the Martian surface evolved into the alteration products seen today. The answers to these questions will tell us about weathering environments, rates of alteration, and climate evolution. The mineralogy of the alteration products is a sensitive indicator of formation conditions such as eH, pH, abundance and phase of water, atmospheric chemistry, temperature, and surface pressure. The presence of different types of iron oxides and oxyhydroxides, carbonates, and clays, and their degree of crystallinity are particularly sensitive indicators of formation conditions and can be characterized by VSWIR spectroscopy. Additionally, the mineralogy of unaltered material needs to be determined in order to separate weathering products derived locally under current conditions from material formed under other conditions. Therefore, we also need to know the mafic mineralogy of the source rock (olivine and pyroxene composition and abundance). Contextual information such as the mineralogy of any weathering rinds on rocks and how it differs from that of the soil and the duracrust will be needed to derive an integrated picture of what processes have occurred and when.

The 0.4 to 2.5  $\mu\text{m}$  region contains diagnostic absorption features of minerals, atmospheric gasses, volatiles, and organics. Clark *et al.* (1990), Swayze (1997), and Swayze *et al.* (2001) studied the spectral sampling and spectral range needed to resolve absorption bands in spectra and discriminate between mixtures. They found that the ability to identify minerals decreases dramatically at a sampling and spectrometer bandpass (Full-Width at Half-Maximum, FWHM)  $>20$  nm, with detection difficulties beginning at  $\sim 15$  nm. Modeling, laboratory mixture work, operational experience and field verification with imaging spectroscopy data (e.g., Clark and Roush, 1984; Clark 1983; Swayze 1997; Swayze *et al.*, 2001; Clark 1999; Clark *et al.* 2001) indicate that important minerals can be detected at abundances of  $<1\%$  per pixel with a SNR  $>200:1$ . However, improved spectral resolution and SNR enable better atmospheric corrections and lower detection limits.

**Spectrometers on Mars Rovers:** The design and building of in situ spectrometers for Martian rovers must be carefully tailored to the platform and mission. Specific site geology and mission goals must be considered. A key factor is matching the instrument to the platform and the resources available. Mass, power, data rate, data volume, platform stability, spatial resolution, and pointing requirements all influence the spectrometer design and how it is used.

Spectroscopy on rovers falls into three broad categories. Panoramic imaging spectroscopy produces complete hyperspectral coverage of the location and thus the complete mineralogy of a site. Point spectroscopy can generate hyperspectral coverage, but it is very time consuming. After an initial assessment point spectrometers raster out small areas targeted via multi-spectral imaging and relate the mineralogy of points to the scene via their visible spectral colors. Microscopic spectroscopy looks at mineralogy of rock grain—basically relating rock texture to composition.

On a rover, the scene changes every time the rover moves. This means that analysis and interpretation of the data must be done in hours to influence the tasks the rover will carry out the next

sol. This type of rapid real time analysis is very different from how most planetary scientists conduct their research. To enable working in this type of environment new analysis tools and approaches need to be developed. Additionally, instrument calibration and performance stability take on a larger importance since artifacts can cause bad decisions to be made.

**Terrestrial Spectroscopy Field Trials:** The Mars Exploration Program is developing technology for future Martian rovers. One area of research is science operations with real instrumentation, including spectrometers. The NASA JPL Field Integrated Design & Operations (FIDO) rover has successfully integrated and validated a point spectroscopy approach using a 1.2-2.4  $\mu\text{m}$  spectroscopy during field trials (Arvidson et al. 2000, Haldeman et al. 2002). In 2001, FIDO field trials were used to model operations of the 2003 Mars Exploration Rovers (MER). Other rovers that use spectrometer data in their field trials include the AMES Marsokhod and K9 rovers (e.g. Stoker et al. 2001).

**Future Directions:** To date most of the research has focused on the 2003 MER whose payload includes the Miniature Thermal Emission Spectrometer (Mini-TES). Mini-TES will be used to determine the mineralogy of rocks that are potential targets of investigation. It will also validate the TES and Themis global remote sensing data sets and interpretations.

The next rover opportunity for will be the 2009 Mars Smart Lander—which calls for a Mobile Science Laboratory. This rover is planned to be nuclear powered and thus operate for substantial periods of time. It will also be the first opportunity to validate the 2005 MRO CRISM imaging spectroscopy data.

Further field trials need to be developed which evaluate instrument types given the differences in resources (power, mass, data rate) between MER and Smart Lander. Additional automation of the analysis and interpretation of spectroscopy data needs to be carried out to sustain long term rover operations affordably.



**SPECTRAL FEATURE MAPPING AND ANALYSIS OF MARS GLOBAL SURVEYOR THERMAL EMISSION SPECTROMETER DATA.** Roger N. Clark, Todd Hoefen, Michael D. Smith, and John C. Pearl

The Mars Global Surveyor (MGS) spacecraft began orbiting Mars on September 11, 1997. After aerobraking and science phasing periods where the orbit shape and equator timing were adjusted, mapping by science instruments began on March 9, 1999. The Thermal Emission Spectrometer (TES) has obtained 6-50  $\mu\text{m}$  spectra of Mars since the mapping period began and continues to do so to the present. The TES obtains nadir pointed spectra of nominal 5 and 10  $\text{cm}^{-1}$  spectral sampling (143 or 286 spectral channels) from 6.25 to 50  $\mu\text{m}$  (1600 to 200  $\text{cm}^{-1}$ ) in 2 to 4 seconds. The TES also obtains limb pointed spectra and selected angles in between nadir and limb, as well as space pointed and internal black body pointed (for calibration) spectra. The TES obtains both day and night side data in a 3-pixel cross track and 2-pixel down track array. The pixel size is 3 km across track and 6 km down track. Six-km down-track smear is caused by orbital motion due to the spacecraft flying backwards from its intended direction and in an orientation where the TES image motion compensation does not work.

Approximately 3 years of MGS TES day-side, nadir-pointed, 10-wavenumber data have been culled from the TES database and projected into image cubes at full TES spatial resolution of  $\sim 3$  km per pixel to provide near global coverage. Coverage of the poles north and south of 60 degrees latitude has not been included in this analysis because of pervasive clouds in the data set at the polar latitudes. Three years of TES data allowed selection of the best spectra, free of artifacts to be assembled and still have  $> 80\%$  surface coverage. Multiple observations of the same area on the martian surface were averaged to provide the overall highest quality spectrum at each pixel.

The image cubes were assembled at 20 pixels/degree, or 2.96 km/pixel at the equator. Thus, for coverage from 60 degrees north latitude to 60 degrees south latitude, the hyperspectral image cubes of Mars comprise 7200 pixels in longitude by 2400 pixel in latitude in a simple cylindrical projection, and 143 channels in the spectral dimension.

The hyperspectral image cubes were calibrated to radiance using internal black-body measurements and space measurements. Apparent emis-

sivity was derived for each pixel using temperatures in the TES database. Finally, atmospheric gas absorptions were removed and ancillary data were registered with the images, including albedo and MOLA topographic elevation.

The data cubes have been analyzed for the presence of spectral features due to surface geology. The analysis of this vast data set of tens of millions of spectra is limited by our present knowledge of the spectral properties of materials in the infrared. The results and analysis implications will be discussed.

Spectral features were searched for using least squares feature analysis with reference spectral library features. The search was limited to regions of the TES spectra free of strong gas and dust absorptions and where TES has high signal-to-noise ratio. This effort represents the most extensive and highest resolution search for minerals on Mars to date, to our knowledge.

The search for minerals, however, is limited by current spectral libraries. Spectral features in the infrared are strongly affected by grain size and few minerals have had spectra measured as a function of grain size.

The most spectrally abundant features found in the TES data to date are those due to pyroxenes, olivine, and hematite. In fact, while some other small and weak spectral features can be seen in the data, only spectral features due to pyroxene, olivine, and hematite have been definitively identified and map in large geologic regions on Mars. Searches for outcrops of other minerals, including carbonates, quartz, and mineral signatures of hydrothermal alteration systems and mineral deposits have failed to definitively show in the TES data. Such minerals, if they exist on Mars, are either significantly smaller than a TES pixel, or are buried by dust. More reference spectra in libraries, and as a function of grain size may lead to identification of more minerals.

Olivine shows variable composition in different regions of Mars, and appears stratified in outcrops at certain elevations. The implications of this stratification are under study but may indicate changing volcanic conditions in martian geologic history, or region or both.

**A COORDINATED LABORATORY PROGRAM IN SUPPORT OF THE SPECTROSCOPIC EXPERIMENTS ON BOARD MARTIAN MISSIONS.** S. Fonti<sup>a</sup>, G. Arnold<sup>b</sup>, A. Blanco<sup>a</sup>, G. Bonello<sup>c,d</sup>, L. Colangeli<sup>e</sup>, M. D'elia<sup>a</sup>, F. De Carlo<sup>a</sup>, S. Erard<sup>c</sup>, F. Esposito<sup>e</sup>, V. Formisano<sup>f</sup>, A. C. Marra<sup>a</sup>, G.A. Marzo<sup>a</sup>, V. Orofino<sup>a</sup>, E. Palomba<sup>e</sup>, G. Piccioni<sup>d</sup>, R. Politi<sup>a,d</sup>, C. Wagner<sup>b</sup> <sup>a</sup>Dipartimento di Fisica, Università di Lecce, Italy<sup>b</sup>; deutsches Zentrum für Luft- und Raumfahrt e.V., Berlin, Germany; <sup>c</sup>Institut d'Astrophysique Spatiale, Université Paris-Sud / CNRS, France<sup>d</sup>; Istituto di Astrofisica Spaziale del CNR, Rome, Italy<sup>e</sup>; Osservatorio Astronomico di Capodimonte, Naples, Italy<sup>f</sup>; Istituto di Fisica Dello Spazio Interplanetario del CNR, Rome, Italy

In recent years the scientific interest for Mars has grown considerably, spurred mainly by the renewed attention of Space Agencies. In particular the successful NASA missions Mars Pathfinder and Mars Global Surveyor (MGS) have supplied a wealth of new data, but at the same time have opened a large number of new questions concerning both the present and the past of the planet (Mars Pathfinder Team, 1997; MGS/TES Team, 2000). It is worthwhile to note that some of the pending issues are considerably appealing also for the general public. As an example we can consider the consequences that the assessment of past existence of liquid water on the surface of the planet can have for the possibility that life has developed on Mars in the past (McKay, 1991; McKay et al., 1996). It is probable that no definite results can be obtained without a direct analysis of samples retrieved from a carefully chosen landing site, but such an occurrence is not scheduled in the near future. Therefore, for the time being, the information obtained with the observation of the planet by means of orbiting instruments, can play an important role in addressing many important questions concerning the climatic evolution of Mars.

In this respect, the Mars Orbiter Camera on board of MGS has demonstrated, beyond any doubt, the extreme usefulness of the visual inspection at high spatial resolution. Nevertheless a complete picture can be reconstructed only comparing the information retrieved in this way with the results obtainable by means of visible and infrared (IR) spectroscopy. However the interpretation of visible and IR spectra is not straightforward and the amount of retrieved information, as well as its reliability, depends strongly on the possibility to relate the observational data with laboratory spectra of suitable materials, carefully chosen among those thought to be analogues to the Martian ones. Therefore the availability of an adequate spectral library for OMEGA and PFS,

the spectrometers on board of the ESA mission Mars Express, planned in 2003 (Chicarro, 1999), is absolutely necessary. In the same way the Arizona State University spectral library has played a major role in the analysis of the spectra obtained by the Thermal Emission Spectrometer (TES) on board of MGS (Christensen et al., 2000).

It is important to realise that the main characteristics of a spectral library has to be tailored following the features of the involved instruments, as well as the peculiarities of the object to be studied. In this presentation the parameters used in defining the structure of the laboratory data set will be described in some detail, together with the requirements needed in order to compare the information contained in the library with spectra available from already existing laboratory data sets. It can be anticipated here that a major constraint is the homogeneity of the collected spectra, involving not only the actual collection of the data, but also the preparation and a thorough characterization of the each sample.

The spectral characteristics of a given material can be retrieved using different techniques: emission, transmission and reflectance and in each case they can be the experimental base for the computation of the optical constants of the examined material (Bohren and Huffman, 1983; Wenrich and Christensen, 1996; Esposito et al., 2000). A spectral library, in order to be used as a reference for the data obtained by OMEGA and PFS, should contain reflection spectra in the range 0.3 – 7  $\mu\text{m}$  and emission spectra in the range 3 – 50  $\mu\text{m}$ , as well as transmission spectra in the whole spectral range, at the appropriate resolution. This would allow using the different spectroscopic techniques for mutual validation and for the derivation of the optical constants in the widest possible range.

The choice of the materials to be examined is a rather complex issue and will be discussed during the presentation. It must be noted, though, that

the problem is further complicated by the presence of dust on the Martian surface and in the Martian atmosphere and by the fact that the spectral properties of a particulate sample depend on the size of the grains particularly when the particles are much smaller than the radiation wavelength, as in the case of the Martian aerosol (Bohren and Huffman, 1983). This occurrence can be used to retrieve additional information from the observed spectra, but, on the other hand, requires a much longer laboratory work, aimed to differentiate the spectral characteristics in function of the grain size.

It should be clear at this point that the task of preparing an appropriate database is well beyond the capability of a single laboratory. For this reason the outlined program will be accomplished through the joint effort of at least five laboratories. The parallel involvement of different experimenters, using the same procedure, but different equipment should allow for a mutual validation of the results. On the other hand, as it will be discussed in the presentation, the coordination of the experimental work must place additional stress on the concept of data homogeneity especially in connection with the preparation procedure of each particulate sample as well as its chemical, elemental and morphological characterization.

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**MAPPING LITHOLOGIC UNITS EXPOSED ON THE SUMMIT OF MAUNA KEA USING AVIRIS HYPERSPECTRAL REFLECTANCE DATA.** E. A. Guinness<sup>1</sup>, R. E. Arvidson<sup>1</sup>, B. L. Jolliff<sup>1</sup>, R. V. Morris<sup>2</sup>, and D. W. Ming<sup>2</sup>, <sup>1</sup> Department of Earth and Planetary Sciences, Washington University, 1 Brookings Drive, St. Louis, MO 63130, <sup>2</sup> Code SN, NASA-Johnson Space Center, Houston, TX 77058.

**Introduction:** The Mauna Kea summit region is largely comprised of cinder cones and lava flows that form the cap of the Mauna Kea Volcano. The cones and flows at the summit are part of the Laupahoehoe Volcanic series. The Laupahoehoe volcanism occurred both during and after the late Pleistocene Makenaka glacial episode at the summit [1]. In addition, a few Laupahoehoe cones have been glacially eroded as evidenced by oversteepened slopes, which suggests that they predate the Makenaka glacial period. Two notable examples of possible preglacial cones are Puu Waiau and Puu Poliahu. These two cones are also significantly altered, most likely by hydrothermal activity that has weakly cemented the materials on the cones [1]. Well-crystalline sulfates (alunite and jarosite), phyllosilicates, and zeolites, have been found in samples collected from altered cones at the summit [1-3]. In addition, palagonitic tephra, which have nanophase ferric oxide, allophane, and other poorly crystalline forms of weakly altered basaltic glass (i.e., no phyllosilicates), have been described at several locations on Mauna Kea [e.g., 4, 5]. While several studies have discussed the occurrence of alteration products on Mauna Kea, the distribution of these materials exposed at the summit has not been extensively mapped.

Hyperspectral imaging can provide information for identifying and mapping lithologic units containing alteration minerals, such as are found on Mauna Kea. The Airborne Visible Infrared Imaging Spectrometer (AVIRIS) is a hyperspectral imaging instrument that covers the wavelength range from about 0.4 to 2.5  $\mu\text{m}$  in 224 bands, with a band spacing of 10 nm and average band width of 10 nm [6]. Reflectance spectra in this wavelength range contain electronic transitions and vibrational absorption features that can be used to identify and discriminate ferric oxide, phyllosilicate, and sulfate minerals typically found in alteration zones. AVIRIS data also provides high spatial resolution with a ground instantaneous field of view of 20 m when flown at its nominal altitude of 20 km above sea level. AVIRIS

was deployed to Hawaii for the first time in 2000 with AVIRIS data acquired over much of the Hawaiian Islands, including the summit of Mauna Kea.

**Methods:** The Mauna Kea summit is covered by a 10 x 10 km AVIRIS scene with a pixel size of about 15 x 15 m. The AVIRIS data are corrected for atmospheric scattering and attenuation and converted to ground radiance coefficient values using the ATREM algorithm [7]. ATREM uses a radiative transfer model to compute atmospheric transmittance of gases and scattering from aerosols. The analyses are also restricted to the portion of the scene above the tree line so as to be essentially free of vegetation. Spectrally distinct endmember classes are extracted from the atmospherically corrected AVIRIS reflectance data. The AVIRIS spectra are divided into visible and near infrared (VNIR) and short wave infrared (SWIR) sections so that electronic transition and vibrational absorption features can be analyzed separately. The VNIR wavelength region provides diagnostic absorption features for ferric oxide minerals such as hematite, goethite, and jarosite, whereas the SWIR region contains features due to hydroxyl-bearing minerals, sulfates, and carbonates. Specifically, the wavelength range of 0.41 to 1.06  $\mu\text{m}$  is used in the VNIR analysis and the range of 2.09 to 2.45  $\mu\text{m}$  is used for the SWIR analysis. Maps showing the distribution of each endmember unit are then generated for the VNIR and SWIR data sets using the Spectral Angle Mapper (SAM) method [8]. This method computes the angle between two spectra by treating the spectra as n-dimensional vectors, with n as the number of AVIRIS bands. The angle is determined from the dot product of two vectors where one vector is an endmember spectrum and the other is the spectrum of a given pixel. Small angles mean that the two spectra are similar. The SAM method depends on the shape of the spectra and not on absolute reflectance values, thus minimizing illumination differences. Pixels are assigned to a given endmember unit if the separation angle is less than an assigned threshold.

**Results:** Atmospherically corrected AVIRIS spectra for visible and near infrared wavelengths of 0.4 to 1.1  $\mu\text{m}$  exhibit electronic transition absorption features related to a suite of ferric oxide units. Spectral features suggest the presence of hematite, palagonite, and possibly jarosite. Three spectrally distinct hematite units are seen in the AVIRIS data in terms of the depth of ferric absorption features with variations likely related to the size of hematite grains. Three units with spectral features related to phyllosilicates were also identified in the AVIRIS data based on metal-OH absorptions in the short wavelength infrared region of 2.0 to 2.5  $\mu\text{m}$ . These three units are characterized by spectral features of kaolinite, montmorillonite, and saponite. Surfaces of relatively fresh, uneroded cinder cones are typically dominated by exposures of the ferric oxide units. These cones exhibit a concentric zoning in the distribution of the hematite units, with the hematite unit having the deepest ferric absorption bands occurring at or near the summit of the cones and units having weaker absorptions being exposed further down the flanks of cones. The palagonite unit is typically exposed at the base of cinder cones and

is more widely located on flow surfaces. Surfaces of eroded cinder cones, such as Puu Poliahu and Puu Waiau, have localized exposures of the three phyllosilicate and possible jarosite units. The montmorillonite unit is the most commonly exposed phyllosilicate unit. In some cases there is zoning among the phyllosilicate units with a core of the saponite unit surrounded by montmorillonite. The kaolinite unit is only found in two discrete exposures on Puu Poliahu with one exposure coinciding with a possible jarosite unit. The phyllosilicate units may reflect localized alteration along small fractures or dikes that focused hydrothermal fluids.

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**STATUS OF REFLECTANCE AND EMISSIVITY MODELS RELEVANT TO MARS STUDIES.**

Bruce Hapke, Department of Geology and Planetary Science, University of Pittsburgh, Pittsburgh, PA 15260, hapke@pitt.edu

The status of theoretical models of the interaction of electromagnetic radiation with planetary regoliths relevant to the interpretation of Martian spectroscopic observations is discussed. Most of the problems have to do with particle size effects, because the physics of light scattering is different, depending on whether the particles making up a medium are larger or smaller than the wavelength. The spectral emissivities of media of large and small particles will, in general, be quite different in ways that often are not predictable.

(1) Martian atmospheric dust consists of particles  $\sim 1\text{-}2\text{ }\mu\text{m}$  in size, and powder of similar sized particles probably covers much of the surface. In the visible and near IR the soil particles may be treated as independent scatterers that are large compared to the wavelength. Theory is in fairly good shape in this case.

(2) The major Martian spectral data base is the TES library of IR spectra, which were obtained mainly from powders whose particle sizes are 0.5-1.0 mm, much larger than the wavelengths

used by TES. However, the surface and aerosol particles are much smaller than the wavelength.

(3) In going from large to small particles there is a contrast reversal in the strength of emissivity bands. In large particles, strong bands have large spectral contrasts and weak bands have small contrasts. In small particles the opposite is true. Also, the band wavelengths shift. Hence, atmospheric dust and surface sand of the same material may have very different spectra.

(4) A powder composed of large particles can be treated as if the particles scatter radiation independently even though they are touching. However, in a powder of small particles in contact coherent effects are important, and this affects the spectra in ways that are poorly understood.

(5) The peroxide coatings that appear to be present on the surfaces of Martian regolith particles may have created a kind of Martian desert varnish that affects the spectra in unknown ways.

**THERMAL INFRARED FIELD SPECTROSCOPY.** L. E. Kirkland<sup>1,2</sup>, K. C. Herr<sup>2</sup>, J. M. McAfee<sup>3</sup>, P. M. Adams<sup>2</sup>, J. W. Salisbury<sup>4</sup>, <sup>1</sup>Lunar and Planetary Institute, kirkland@lpi.usra.edu; <sup>2</sup>The Aerospace Corporation, kenneth.c.herr@aero.org, paul.m.adams@aero.org; <sup>3</sup>Los Alamos National Laboratory, mcafee\_john\_m@lanl.gov, <sup>4</sup>Johns Hopkins U. (retired), salisbury@worldnet.att.net.

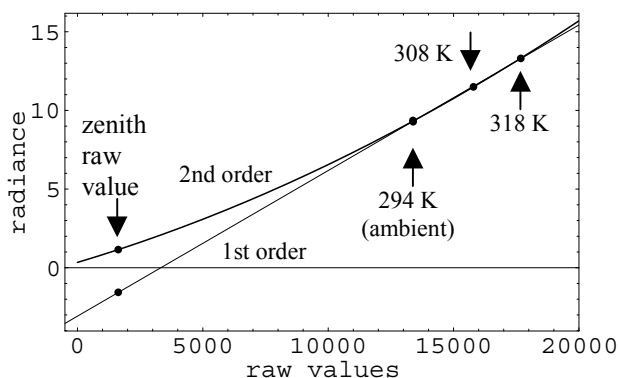
**Introduction:** The 2003 Mars Exploration Rover science strategy calls on Pancam and Mini-TES to identify promising targets for the rover, which will then traverse to those targets for examination. Team members will select sites using target morphology and color (Pancam), and interpretations of the mineralogy using Mini-TES.

This strategy requires high quality, near real-time interpretations of Mini-TES data. The planetary community has essentially no experience with rapid identification using field images measured similarly to Mini-TES. Department of Defense researchers have instrumentation, data sets, and experience in this area. Here we discuss lessons learned in interpreting field spectra and measurement protocols that improve interpretations. We solicit input for what targets and sites to measure using our hyperspectral field scanners for release to the community.

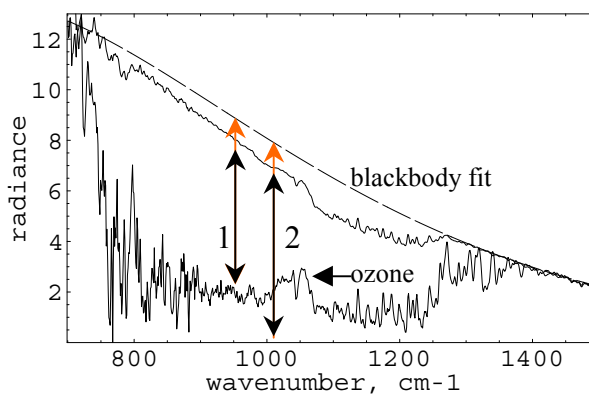
**Instrumentation:** The Aerospace Corporation owns the equipment we use. This includes Block Engineering Model 100 (M100) Fourier transform infrared interferometers mounted on three types of van platforms. The M100 measures hyperspectral images using a precisely controlled mirror that raster scans in two dimensions at 25 Hz, and it records the viewing angles with the data. The viewing geometry and scanning system are very similar to the Mini-TES (Table 1).

**Extracting signatures:** First the data are *calibrated* to radiance. Fig. 1 shows a calibration curve measured in the field, at 989 cm<sup>-1</sup>, using blackbodies at 294, 308, and 318 K, and 1<sup>st</sup> and 2<sup>nd</sup> order polynomial fits. The calibration works well over the temperature range of the calibration targets, but Fig. 1 illustrates why it is difficult to extrapolate to cold values (e.g. sky spectra).

Second, the data must be *converted* to a unit for comparison to laboratory data. Fig. 2 illustrates a conversion to apparent emissivity. When the diffuse downwelling radiance is not known, apparent emissivity uses zero as the zero emissivity reference line (Arrow 2), and is the measured radiance divided by a blackbody fit. When the diffuse downwelling radiance is known, it is used as the zero emissivity reference line (Arrow 1). This is called a special ratio [1], given by (measured-downwelling) / (blackbody fit-downwelling). Fig. 3 shows both results.



**Fig. 1: Calibration curve.** This illustrates the difficulty in extrapolating to cold brightness temperatures using only warm calibration targets. X-axis shows raw data, and Y-axis the blackbody radiance values calculated at the measured calibration target temperature and compensated for the true target emissivity. Radiance units are W/cm<sup>2</sup> sr cm<sup>-1</sup> multiplied by 10<sup>6</sup>. (From scene 0209-048.)

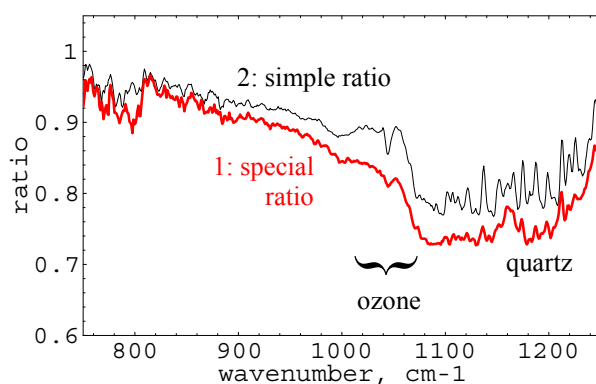


**Fig. 2: Field spectra.** The upper curve is a blackbody fit to the highest brightness temperature over 820–1278 cm<sup>-1</sup>; the middle trace was measured of a quartz-rich region, and the lower trace of a diffuse aluminum target that has been adjusted for the laboratory measured reflectance (~90%). Arrow 1 illustrates a ratio compensated for downwelling radiance (“special ratio”), and Arrow 2 shows a simple ratio. We used a second order calibration curve (Fig. 1) to prevent negative radiance values for the cold diffuse downwelling spectrum. (Radiance units: W/cm<sup>2</sup> sr cm<sup>-1</sup> × 10<sup>6</sup>). Scene 0424-216)

**Table 1: Instrument parameters**

	FOV (mrad)	el (deg)	az (deg)	sampling (cm <sup>-1</sup> )	range (μm)	height (m)
Mini-TES[2]	20 or 8	-50 to +30	360	10	5–25	~1.4
M100	8.7	-70 to +90	360	2	7.5–13.5	~2, 2.5, 3

FOV = field of view; el, az = elevation, azimuth range; sampling = spectral sampling interval; range = spectral range; height is above ground



**Fig. 3:** The “special ratio” and “simple ratio” show the ratios marked by Fig. 2, Arrow 1 and 2, respectively. Most fine spectral details evident are atmospheric features. The special ratio compensates for the downwelling radiance, but the residual ozone doublet shows the compensation here is incomplete, probably because the aluminum target was tilted, not perfectly diffuse, and/or from the calibration extrapolation. Residual downwelling radiance signatures will affect mineralogy interpretations. This will be important for Mini-TES because of downwelling aerosol radiance and the lack of a diffuse target to measure the downwelling radiance. (Scene 0424-216)

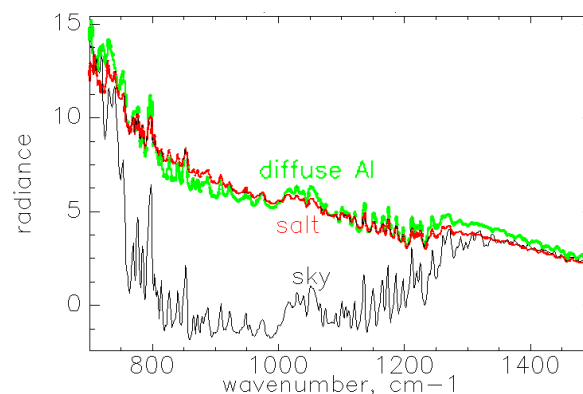
Conversions for TES use a simple ratio. However, field data have greater atmospheric downwelling radiance contribution than airborne or satellite measurements (because gases absorb where they emit). Our experience is that our airborne hyperspectral data have not required a downwelling radiance compensation for a high quality conversion, but our field spectra do. Similarly for Mars, we should not be lulled into thinking reflected downwelling radiance is unimportant for Mini-TES because it seems unimportant for TES.

The downwelling radiance is best measured using a diffuse, high reflectance target, particularly for materials near other objects. Direct, line-sight measurement of the sky does not accurately record the diffuse downwelling radiance, and our experience is that it is a poor substitute (Fig. 4). The latter is approach is planned for Mini-TES, and the results should be simulated and examined.

**Issues for Mini-TES:** Our experience with field spectrometers is that the full interpretation chain has many potential sources of error. Difficulties include (1) calibrating to cold brightness temperatures; (2) diffuse, specular, and partial mixing of target and downwelling radiance; (3) determination of diffuse downwelling radiance from direct sky measurements; (4) near real-time interpretations combined with lack of practice data and experience; (5) field signatures are frequently more subtle than laboratory signatures, so practice with field signatures is required to gain the experience to interpret field data accurately; (6) incomplete supporting spectral libraries, particularly of rough, weathered, coated, very fine, and mixed materials.

For Mars, incompletely compensated aerosol dust downwelling radiance can alter interpretations, par-

ticularly for silicates. The dust distribution with altitude will affect the magnitude of the contribution. Water ice clouds will also contribute, and the diffuse contribution may be particularly difficult to determine when the cloud coverage varies during direct sky measurements by Mini-TES.



**Fig. 4:** The “diffuse Al” trace shows a spectrum measured of a diffuse aluminum target, compensated for the true reflectance; the “salt” target is ~5 mm rock salt particles; and “sky” shows a point measurement of the sky near zenith. Note that diffuse and line-sight downwelling radiance differ significantly. We measured this scene at a more humid location than in Fig. 1. Negative radiance values illustrate the difficulty in extrapolating from warm calibration targets to very cold brightness temperatures. Here we used a first order fit. (Units:  $\text{W}/\text{cm}^2 \text{ sr cm}^{-1} \times 10^6$ ). Scene 0209-048.

Data sets measured similarly to the Mini-TES are critical to have to understand these issues; to develop and test measurement protocols and near real-time and in-depth interpretation methods; and so the instrument team and community can prepare to interpret the Mini-TES data. Lab, airborne/satellite, and single-point field spectra alone are not sufficient because they do not simulate all the critical effects present. Test data sets should include natural scenes to force consideration of unexpected effects, and constructed scenes to extend materials measured (e.g. very fine particles and coatings). Scenes covering the full wavelength range of Mini-TES should also be simulated by seaming with laboratory spectra. They should be degraded to the expected signal-to-noise ratio of the Mini-TES and interpreted both near real-time and more in-depth. The full calibration, conversion, and interpretation chain should be tested near real-time using those data sets and the same measurement protocols as planned for Mini-TES.

Finally, we have found that it is critical to include a known target with good spectral contrast in our field images to test the full chain. Without this reference, it is impossible to evaluate the result. Mini-TES can use targets of opportunity (e.g. airbags) if those targets are measured pre-flight.

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**MARTIAN ANALOGUE SAMPLE CHARACTERIZATION AND SPECTRAL LIBRARY DEVELOPMENT AT THE JOHNSON SPACE CENTER.** Richard V. Morris, Astromaterial Research and Exploration Science Office, NASA Johnson Space Center, Houston, TX 77058.

**Introduction.** An extensive collection of Martian analogue samples housed at the Johnson Space Center is the focus of ongoing research by the JSC Mars soil genesis group and their collaborators [e.g., 1]. Because the major element composition of Martian meteorites and in situ analyses of Martian soils and rocks indicate that Mars is predominantly an iron-rich basaltic world, the focus of active sample collection and analysis is basaltic materials and their hydrolytic (both aqueous and hydrothermal) and sulfatetic alteration products. Described below are the scope of the JSC Mars analogue sample collection, the characterization process, and plans to incorporate the data into spectral libraries for the Mars 2003 Mars Exploration Rover (MER) and Mars 2005 Mars Reconnaissance Orbiter (MRO) CRISM missions.

**Samples and Characterization.** The JSC Mars analogue sample collection has 1000-1200 individual samples of rocks, soils, and minerals. Because these samples have been subdivided into 2 to 8 size and/or magnetic separates, the number of samples with distinct physical, chemical, and mineralogical properties is on the order of 3000. Examples of the variation of chemical and mineralogical composition for size and magnetic separates of palagonitic and sulfatetic tephra from Hawaii are given by [1, 2, 3].

Our standard set of characterization analyses includes major elemental analyses, diffuse reflectance spectroscopy between 350 and 2100 nm under desiccating conditions, Mössbauer spectroscopy, X-ray diffraction, and magnetic properties (magnetic susceptibility and saturation magnetization). Most of these analyses have been completed for ~1000 samples. Solution pH and electrical conductivity measurements have been com-

pleted for ~300 soil samples. Thermal emission spectra (200-2000  $\text{cm}^{-1}$ ) have been measured for ~400 samples at Arizona State University. The analytical techniques were selected to both characterize the samples and to maximize overlap with current and future remote sensing and in situ data for Mars.

**Samples and Spectral Libraries for Planetary Missions.** Part of the JSC Mars analogue sample collection is a set of well-characterized rock slabs. The purpose of these slabs is to validate the calibration and performance of flight instruments. Rock slabs, rather than particulate samples, are used because they present reproducible surfaces for measurement to flight and laboratory instruments. These samples have already been used with CONTOUR and Mars Express OMEGA flight instruments and the mini-TES and Mössbauer MER instruments. The slabs will be used with the other MER analytical instruments (APXS, PANCAM, and MI) and with the CRISM MRO 2005 instrument.

Current plans are to publish the spectral and characterization data for JSC Mars analogue samples on a JSC-based WEB site. For full use with MRO, the JSC Mars analogue samples will require characterization under desiccating conditions in the spectral region between 2 and 5  $\mu\text{m}$ . Work is underway to increase the number of samples in the  $<5 \mu\text{m}$  size fraction by size separations of soils and pulverization of rocks. The  $<5 \mu\text{m}$  size fraction corresponds to the size fraction for aeolian dust on Mars [e.g., 4].

**References.** [1] Morris et al., JGR, 105, 1757, 2000; [2] Morris et al., JGR, 106, 5057, 2001; [3] Morris et al., GCA, 57, 4597, 1993; [4] Markiewicz et al., JGR, 104, 9009, 1999.

# CRISM: COMPACT RECONNAISSANCE IMAGING SPECTROMETER FOR MARS ON THE MARS RECONNAISSANCE ORBITER.

S. Murchie<sup>1</sup>, R. Arvidson<sup>2</sup>, O. Barnouin-Jha<sup>3</sup>, K. Beisser<sup>1</sup>, J.-P. Bibring<sup>3</sup>, J. Bishop<sup>4</sup>, J. Boldt<sup>1</sup>, T. Choo<sup>3</sup>, R.T. Clancy<sup>5</sup>, E.H. Darlington<sup>3</sup>, D. Des Marais<sup>4</sup>, D. Fort<sup>1</sup>, J. Hayes<sup>3</sup>, J. Lees<sup>1</sup>, E. Malarret<sup>6</sup>, D. Mehoke<sup>3</sup>, R. Morris<sup>7</sup>, J. Mustard<sup>8</sup>, K. Peacock<sup>3</sup>, M. Robinson<sup>9</sup>, T. Roush<sup>4</sup>, E. Schaefer<sup>3</sup>, P. Silverglate<sup>1</sup>, M. Smith<sup>10</sup>, P. Thompson<sup>3</sup>, and B. Tossman<sup>1</sup>, <sup>1</sup>Applied Physics Laboratory, Laurel, MD 20723, <sup>2</sup>Washington University, St. Louis, MO, <sup>3</sup>Institut d'Astrophysique Spatiale, Orsay, France, <sup>4</sup>NASA/ARC, Moffett Field, CA, <sup>5</sup>Space Science Institute, Boulder, CO, <sup>6</sup>Applied Coherent Technology, Herndon, VA, <sup>7</sup>NASA/JSC, Houston, TX, <sup>8</sup>Brown University, Providence, RI, <sup>9</sup>Northwestern University, Evanston, IL, <sup>10</sup>NASA/GSFC, Greenbelt, MD.

**Introduction:** The Compact Reconnaissance Imaging Spectrometer for Mars (CRISM) on the Mars Reconnaissance Orbiter (MRO) will conduct a comprehensive series of investigations of the Martian surface and atmosphere. The investigations will be accomplished using an instrument design that provides high spatial and spectral resolutions, extended wavelength range, and ability to gimbal through a range of orientations. Baseline investigations include a near-global survey to find high science priority sites, full-resolution measurement of thousands of such sites, and tracking of seasonal variations in atmospheric and surface properties.

**Science Overview:** The Mars Exploration Payload Analysis Group [1] recommended specific hyperspectral imaging investigations to characterize Martian geology, climate, and environments of present or past life. CRISM's three groups of investigations address all of MEPAG's recommendations. The first two groups correspond to two primary objectives of MRO: *to search for evidence of aqueous and/or hydrothermal activity, and to map and characterize the composition, geology, and stratigraphy of surface features*. These investigations are implemented by high-resolution hyperspectral mapping of thousands of high priority targets including candidate sedimentary deposits [2], volcanic regions, crustal sections exposed in steep escarpments, and sites which exhibit evidence in Mars Express/Omega data for concentrations of aqueously formed minerals. The third group of investigations addresses the primary MRO objective *to characterize seasonal variations in dust and ice aerosols and water content of surface materials, and the secondary objective to provide information on the atmosphere complementary to other MRO instruments*. These investigations are implemented using a systematic, global grid of measurements of the emission phase function (EPF) acquired repetitively throughout the Martian year. EPF measurements allow accurate determination of column abundances of water vapor, CO, dust and ice aerosols, and their seasonal variations [3]. At the same time, the grid's repetitive coverage will track seasonal variations in water content of surface material. Additional, targeted observations of the polar caps will investigate their inventory of water and CO<sub>2</sub> ices.

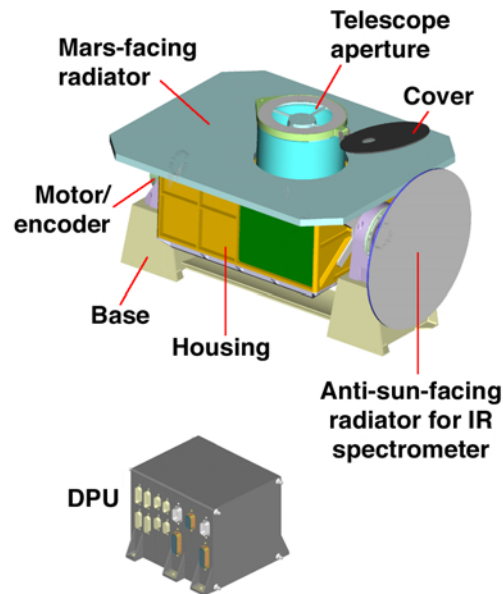
When not taking targeted measurements, CRISM will conduct a ~100 m/pixel, ~59-wavelength survey to search for evidence of aqueous activity that lacks morphologic expression and/or is below the resolution of previous spectral mapping. The survey addresses MRO's secondary objective *to identify new sites with high science potential for future investigation*, and will be particularly important for identification of key Noachian deposits. For example, even at low Martian erosion rates [4], morphologic expressions of Noachian hot spring deposits would have been removed in ~109 yrs, so that such deposits may now exist only as mineralized spots in morphologically unremarkable eroded escarpments, crater ejecta, and talus. Much of the survey will be completed before MRO's highest downlink rates, so that newly discovered sites can be targeted with full-resolution coverage.

**Instrument Overview:** An overview of the instrument is shown in **Figure 1**. CRISM's two major subassemblies are the Optical Sensor Unit (OSU) and the Data Processing Unit (DPU). The OSU contains visible (VIS) and infrared (IR) imaging spectrographs that share the same 2.05° field-of-view and cover the wavelength ranges 400-1050 nm and 1050-4050 at 7 nm/channel. The IR focal plane is cooled with doubly redundant cryogenic coolers. A side-facing radiator cools the spectrometer cavity to decrease instrument background. An onboard integrating sphere provides radiance calibration, and a shutter and dedicated dark pixels on each focal plane provide background measurements interleaved with Mars measurements. Optics and the focal planes are enclosed in a housing that is gimballed by a high-precision motor/encoder ±60° along-track from nadir. During measurement of a target, along-track scanning takes out most groundtrack speed and allows long integration times and high signal-to-noise ratio (SNR) data to be obtained. At the same time, scanning provides the capability to remeasure a spot repeatedly at multiple emission angles to characterize the EPF. High spatial resolution (~18 m/pixel from 300 km altitude) allows characterization of the surface at the outcrop scale, and wavelength coverage to >4000 nm provides sensitivity to carbonates even at low abundances. The DPU provides lossless or lossy compression of the data stream in real

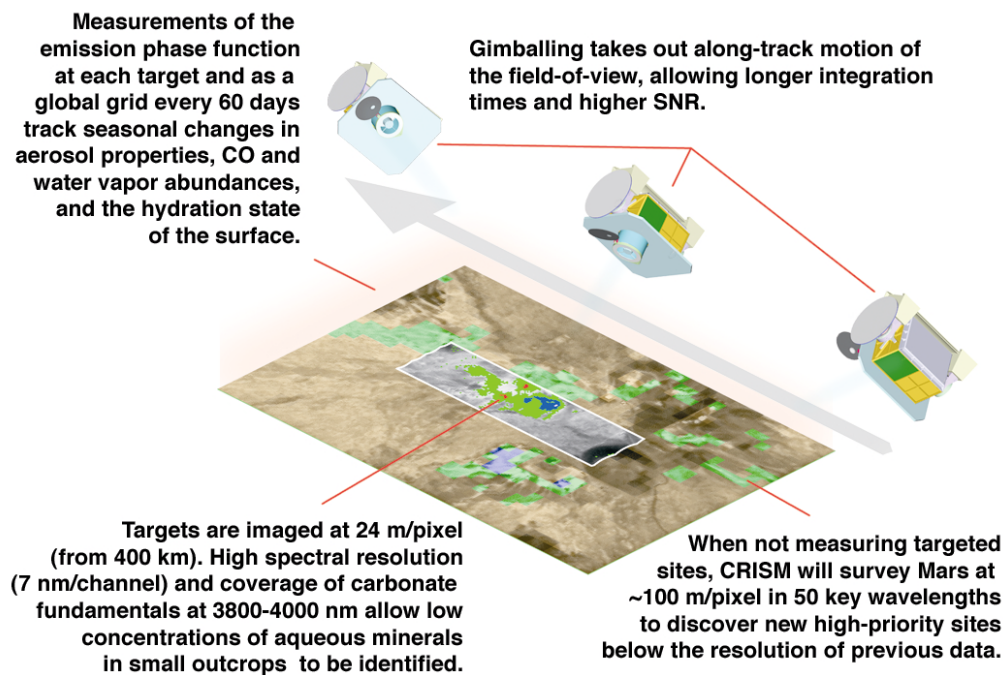
time. Key design elements are adapted from the CONTOUR and MESSENGER optical instruments.

**Operations Overview:** Figure 2 summarizes CRISM's three complementary data acquisition strategies, which are built around the three steps needed to characterize high scientific priority, small-scale deposits: find the deposits, separate their signature from that of the atmosphere, and acquire high spectral and spatial resolution measurements with high SNR. Most of the time the OSU views nadir, building up coverage in multispectral survey mode. In the second mode of observing, for a group of ~36 orbits once every ~30° of Ls, EPFs are measured on a 10° longitude x 15° latitude grid. The third mode is targeted observations, approximately 2200 of which will be obtained at key locations. At each site, gimbaling is used to take out most along-track motion, so that the field-of-view is slowly scanned over a rectangular swath approximately 11 km wide (when measured from 300 km altitude). Measurements of the swath are bracketed by incoming and outgoing measurements of the EPF of the center-point of the swath at emission angles up to  $\pm 60^\circ$ . Larger high-priority targets will be identified in Mars Express/Omega data and other data sets. The multispectral survey provides redundancy to Omega data in locating targets that have VIS-IR spectral signatures but lack obvious morphologic expressions, and it provides the spatial resolution needed to identify small targets not evident in Omega data.

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**Fig. 1.** Preliminary CAD renderings of CRISM's OSU and DPU.



**Fig. 2.** Schematic depiction of key attributes of CRISM's measurement plan for the Martian surface and atmosphere.

**REVIEW OF THE ISM INSTRUMENT AND RESULTS.** John F. Mustard, Department of Geological Science, Box 1846, Brown University, Providence RI, 02912. (John\_Mustard@brown.edu) #3040

**Instrument Parameters:** Detailed descriptions of the ISM instrument are provided by [1,2,3,4, 5] and a detailed web site with access to the ISM data can be found at: [www.ias.fr/cdp/Base\\_ISM/INDEX.HTM](http://www.ias.fr/cdp/Base_ISM/INDEX.HTM). The ISM instrument is a scanning imaging spectrometer that covers the spectral range 0.76 to 3.16  $\mu\text{m}$ . For each pixel, 128 spectral measurements are acquired simultaneously. A 2-dimensional image of the surface was obtained by rotating the entrance mirror to scan in the cross track direction for the image samples and the forward motion of the spacecraft provides the image lines. The spectral dispersion is obtained by using a grating, whose the first and second orders are exploited. These two orders are separated by a beam-splitter and filters, and measured by four groups of 32 cooled PbS detectors, designated first and second order odd and even. Extensive evaluation of data quality and integrity has shown that the even detectors are superior overall to the odd detectors [4]. Therefore the even channels for the first and second order are used which results in 64 channel spectra for each pixel. The signal to noise of these data is extremely high and averages greater than 500:1 for data from 0.77 to 1.51  $\mu\text{m}$  and 1.68 to 2.6  $\mu\text{m}$ . The detector sensitivity drops off slightly at the extremes of the wavelength ranges, but only drops below 100:1 at wavelengths longer than 2.6  $\mu\text{m}$ .

The ISM experiment acquired 11 imaging spectrometer data sets for the surface of Mars. These data sets, or windows, are 24 samples wide and up to 120 lines long. The IFOV of the instrument is  $12' \times 12'$  which, from the altitude of orbit of 6300 km, corresponds to a surface resolution of approximately  $22 \times 22$  km at normal incidence. In the rest position, the viewing plane of the instrument was oriented parallel to the sun's rays and therefore at the subsolar point, the incidence angle equals the emergence angle and the phase angle is  $0^\circ$ . The scanning mirror permits some variation from this geometry and the phase angle varies  $\approx 5^\circ$  for each window and is always less than  $20^\circ$ . Incidence and emergence angles are a function of longitude and latitude. The image data for a given window were acquired over a period of 25 minutes and therefore the effects of temporal variability in the atmosphere are minimal. There is a systematic increase in atmospheric path length with distance from the subsolar point.

**Strengths of the Data Set:** At the time the data were acquired, ISM constituted the first imaging spectrometer data set acquired of another planet from orbit. The key strengths were the contiguous spatial pixels, the imaging format, and most importantly the SNR. The importance of the imaging format cannot be over-emphasized, as this allowed checking of spectral fea-

ture mapping, and mapping of spectral properties of the surface across boundaries and geologic units. The calibration of ISM has been extensively studied and refined over time [4, 6, 7], but what allowed this to a large extent was the very high quality of the acquired data. However, the very high SNR allowed many analyses of relative surface spectral properties to proceed regardless of calibration.

**Significant Results:** There have been 39 peer reviewed publications which concentrate on the data from the ISM spectrometer for Mars and Phobos [5] covering topics ranging from the atmosphere (including composition, aerosols, and variability), to the surface composition (mafic mineralogy, hydrated mineralogy, unusual materials), to the scattering of the surface. Important null results were the lack of any carbonate, sulphate, scapolite, or distinct clay features.

**Atmosphere:** The atmospheric opacity during the mission was uniformly low, estimated to be 0.2-0.3 [8, 9] while atmospheric  $\text{H}_2\text{O}$  showed a diurnal variability [10]. Detailed studies of aerosols revealed several important properties [7]. Scattering by aerosols and dust in the atmosphere is a function of atmospheric opacity and the ISM data were acquired during the period when atmospheric opacity is generally at its lowest. The magnitude and spectral characteristics of the atmospheric scattering were derived for the ISM data using two methods. The first used several spectra that were obtained of the limb permitting direct measurement of atmospheric scattering. The second method made use of regions which were measured during different observing runs. The results of this analysis are that the aerosol particles have an average radius of  $1.2 \pm 0.2 \mu\text{m}$ . The spectrum of the aerosol contribution is dominated by a negative continuum slope which decreases exponentially toward a minimum near 2.6  $\mu\text{m}$ . In addition, the spectral properties revealed a component of water ice, likely associated with atmospheric dust particles.

The total relative contribution to the surface signal is estimated to be 5-15%. Since this scattering is additive, analysis of differences in spectral slope between terrains due to surface spectral properties through derivatives (e.g. [6, 11]) is valid. This scattered component affects the position, shape and strength of mineral absorption features in two ways. First, absorption band strength is reduced which may explain why important crystalline ferric absorptions are observed at some times (e.g. [12]) but not others (e.g. [13,14]). The second effect is to cause an apparent shift to longer wavelengths of absorption band minima. This shift is small ( $\approx 10$ -30 nm) and does not significantly change previous analyses of surface composition from ISM data, but should be factored into future analysis of

surface composition from absorption band position and shape.

**Mineralogy of Low Albedo Regions:** The high spatial resolution, spectral coverage, and high signal to noise of the ISM data permitted the determination of a mineralogic basis for the spectral properties of several distinct morphogeologic dark regions on Mars [15, 16]. Through the use of the Modified Gaussian Model, it was shown that these areas are dominated by two-pyroxene basalts, analogous to the basaltic SNC meteorites, but that the plateau plains (e.g. Syrtis Major) are enriched in high-calcium pyroxene relative to the floors of Valles Marineris. Within this two-pyroxene model, there exists significant diversity in the spectral properties among relatively un-altered regions on Mars, and a central question is how is this spectral diversity related to mineralogic diversity. Then, once we understand the mineralogic composition, what does that tell us about volcanic processes and the composition of the source regions. Ultimately, however, the presence of two-pyroxene basalts implies they were derived from mantle depleted in aluminum relative to the original mantle composition inferred for Mars.

**Mineralogy of Bright and Transitional Regions:** While bright regions show a greater homogeneity than dark regions, they also exhibit important information related to their mineralogy. Murchie et al. [17, 18] showed that the bright regions are largely consistent with the nanophase hematite model in an amorphous silicate matrix. However, most regions exhibited a very weak 2.2  $\mu\text{m}$  feature consistent with a metal-OH band. Some regions, however, did not show this feature. In addition, there are significant variations in the strength of the water of hydration band near 3.0  $\mu\text{m}$ , where layered terrains in Valles Marineris exhibited the strongest absorptions [18]. Finally, many of the so-called dark red regions (e.g. Oxia Palus) exhibited features inconsistent with a simple mixture between bright and dark soils. Rather, they appear to be a unique material and may contain hydrated ferric oxides and oxyhydroxides [18].

**Weak Points of the Instrument and Data Set:** Perhaps the single largest problem to plague the ISM data set was calibration. There are several reasons for this. First, the instrument did not have as extensive an instrument check out as it could have. This is not a criticism of the personnel at IAS who did a remarkable job under a very tight schedule. However, several problems were revealed once the instrument arrived in orbit and it was necessary to conduct numerous analyses to identify and correct calibration problems. While these operations were ultimately successful, it resulted in a distrust of the data set by the larger community. Nevertheless, two studies showed an excellent agreement between ISM and independently acquired spectral data sets [19, 20]. Another weakness was spectral resolution. Although the instrument did have 128 channels, only 64 were used due to pointing and cali-

bration. In addition, slight channel-to-channel offsets created artifacts in limited spectral regions at particular albedo boundaries. Finally, the lack of visible spectral information seriously hampered the ability to understand the ferric mineralogy and separate it from ferrous mineralogy.

**Lessons Learned:** ISM demonstrated the great value of imaging spectroscopy for Mars exploration. Despite the calibration criticisms, and the fact the Mars is remarkably homogeneous on a global scale, much important information was obtained. The extraordinary SNR permitted on-orbit refinement of the calibration and the mapping of extremely subtle spectral differences on the planet. The most exciting features that unfortunately could not be pursued due to the lower SNR were in the water bands near 3.0  $\mu\text{m}$ . There were distinct variations on the surface related to geologic features, but were slightly beyond the spatial and spectral resolution. In my opinion, these are the most important items to consider for future missions:

- Signal to noise...sacrifice spectral and spatial resolution for signal to noise (to a point).
- Spectral range...cover the visible and near-infrared out to the 4.0 CO<sub>2</sub> band
- Spectral resolution...at least 10 nm in key wavelength regions.
- Calibrate, calibrate, calibrate! This includes absolute measures of radiance, and removal of the atmosphere.
- Consistent, coherent variations in martian spectral properties were observed for which we have limited knowledge of how to interpret (e.g. spectral slope). We should be prepared to identify spectral variations related to the surface for which we have a poor understanding of their origin, and devise approaches to solve them.
- We must be prepared to analyze extremely subtle spectral features, have confidence that they originate from the surface reflectance, and design approaches to understand them.

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**METHODS OF SPECTRAL ANALYSIS.** John F. Mustard, Department of Geological Science, Box 1846, Brown University, Providence RI, 02912. (John\_Mustard@brown.edu)

**Introduction:** Spectral analysis refers to the extraction of quantitative or qualitative information from reflectance or emission spectra based on the albedo and wavelength dependent reflectance properties of materials. The goal of this abstract is to highlight some of the major areas of spectral analysis and discuss their relative levels of maturity. There is no single, universally accepted methodology for spectral analysis and frequently the specific methodology used in a given investigation is optimized for the particular objectives, or used because that is what the data allow. The most effective techniques are those with solid foundations in the basic principles of reflectance and emission spectroscopy and thus are more readily transported from one investigation or data set to another. Within the diversity of techniques, we can generalize three basic categories of spectral analysis: definition and mapping of broad-scale units, identification of the presence of specific mineralogic assemblages or lithologic units, and quantification of the amount and properties of material present. The techniques for spectral analysis progress from simple techniques, suitable for discriminating different units but not necessarily providing compositional determinations, to precise deterministic techniques that require high spectral resolution and fidelity as well as a solid foundation in spectroscopic principles. The content of this abstract has been abstracted from a recent review chapter of this subject [1] and relevant references may be found there.

**Definition and Mapping of Broad-scale Units:** The definition and mapping of broad-scale units can be accomplished through the use of simple spectral analysis techniques (e.g. color composites, band ratios, principal components analysis). Units are defined on the basis of shared textural and spectral properties as exhibited in data, where there is a defined spatial coherence to the variables or parameters. Examples for Mars include the bright red, dark red, and dark regions defined by Viking color data, or the regions with common spectral slope defined by ISM. Though some underlying physical basis can be identified, the specific compositional properties of the units may not be determined uniquely.

**Identification of Specific Minerals, Assemblages or Lithologic units:** This requires spectral analysis techniques that are based on the principles of reflectance spectroscopy. When the number of spectral channels is small (e.g. multispectral data) determination of broad mineral and surface compositional classes is possible (e.g. with Pathfinder data regions likely to be enriched in ferric minerals were identified). With high spectral resolution data and spectral coverage spanning a range that includes many individual absorption bands such that the spectral properties are well defined (e.g. ab-

sorption band shape, strength), then a determination of mineral type and composition, mineral assemblage, and lithology is possible. Typically the methods for detailed characterization require ground truth information in the form of a spectral library which is representative of the materials expected on the surface.

**Quantification of the Amount of Material:** The most precise analyses seek to quantify the abundance and texture of minerals present. Natural processes can lead to complex arrangements of minerals. Understanding the variations in mineral abundance due to magmatic or hydrothermal processes, or eolian redistribution of minerals in soils and regolith requires accurate abundance determination that is spatially explicit. Mixture modeling has been shown to be successful for such applications. Other situations are not so straight forward. For example, weathering of rocks creates rinds of altered minerals surrounding fresher rock in the interior and it would be important to determine that the minerals present and their physical association. Such situations have been notoriously difficult to characterize and analyze with classification algorithms, but are highly amenable to spectral modeling.

**Approaches to Spectral Analysis:** A wide range of approaches exist to extract compositional information from remotely sensed data. I have grouped those into a) simple approaches, b) feature mapping and identification of minerals, c) full spectral mapping, d) mixture modeling, and e) spectral modeling. Brief overviews of these approaches are presented below.

**Simple Approaches:** The simplest approach is photo interpretation using color composites. Combinations of spectral bands chosen to maximize contrast among surface materials can be a highly effective approach to data analysis. Band ratios or combinations of band ratios can also be effective, if the ratios are linked to spectral properties of interest. For the Earth, the Normalized Difference Vegetation Index  $((B2-B1)/(B2+B1))$  is a stable and well understood measure of the red edge in vegetation and is related to the concentration of vegetation and other ecologically significant parameters. When ratios are applied with good spectroscopic knowledge, they can be rapid, robust tools for analyzing surface spectral properties, but are not diagnostic.

Statistical transforms have been shown to be effective in identifying relationships among data that differ in subtle ways from one another. This is true for spectral data where there is a high degree of correlation band to band. Among the many possible transforms, Principal Components Analysis (PCA) and the Minimum Noise Fraction (MNF) are the most widely used in spectral analysis. The strength of these approaches is in identifying the dimensionality of data (e.g. there may be 200

spectral channels, but only 10 dimensions) and linear relationships between bands. The weaknesses are that the results depend on the input data and are thus not generally transferable, and the results may be difficult to interpret. There has been some success in relating eigenvectors from statistical transforms to sample chemistry through regression models.

**Feature Mapping and the Identification of Minerals:** The identification and mapping of specific minerals is one of the great strengths of spectroscopy. An important distinction of this type of approach from those presented in the proceeding discussion is that feature mapping and mineral identification is physically based. It exploits the fact that many minerals exhibit absorption bands that are diagnostic of mineral type and composition. By linking to ground truth such as a spectral library, robust identifications are possible. There are three basic approaches to mapping and analyzing mineral absorption features: characterization of the position, strength, and shape of absorption features, correspondence of the complete shape of absorption features from a remote data set to those in a spectral library or data base, quantitative deconvolution of overlapping and superimposed absorptions using an absorption model.

**Full Spectral Mapping:** There are two general classes of approaches to mapping based on the entire spectral signature. The first group of methods are spectral similarity searches. Under a spectral similarity search, a scene is examined to determine which pixels are most "similar" to a specific spectrum of interest or reference spectra. There are numerous ways of objectively defining the "similarity" between two spectra, all of which can be used to produce spectral similarity maps. One of the most widely used is the Spectral Angle Mapper where each spectrum is presented as a vector in  $n$ -dimensional space (where  $n$  is the number of wavelengths) and the angle between each spectrum and the target spectrum is calculated. Small angles equal a good match. A second category of mapping methods that uses the full spectral response are spectral detectors or matched filters. Here a spectrum of interest is detected in a scene by simultaneously highlighting pixels with similar spectral properties while repressing all other background spectral signatures. Spectral detection maps can be produced by many approaches, each of which is based on a different characterization of the spectrum of interest and the background. This kind of approach is particularly useful in identifying materials that differ in subtle ways from the background or have a low probability of occurrence.

**Mixture Modeling:** The basic premise of mixture modeling is that within a given scene, the surface is dominated by a small number of common materials that have relatively constant spectral properties. If most of the spectral variability within the scene is a result of varying proportions of these common components (endmembers), it follows that the spectral variability captured by the remote sensing system can be modeled by mixtures of these components. The spectral mixing systematics are basically linear if the components are ar-

ranged in spatially distinct patterns, analogous to the squares on a checkerboard. In this case the spectrum of a mixed pixel is a linear combination of the endmember spectra weighted by the areal coverage of each endmember in the pixel. If, however, the components of interest are in an intimate association, like sand grains of different composition in a beach deposit, then the mixing systematics between these different components are nonlinear. The spectral properties of the different endmembers become convolved in this case, because the electromagnetic radiation interacts with more than one endmember as it is multiply scattered in the surface.

The validity of spectral mixture analysis has been verified in laboratory, field, and remote sensing studies. The key issues are uniqueness (e.g. difficult to separate spectrally similar materials), the number of endmembers permitted, and accommodation of spectral diversity not due to mixing. Strategies have been developed to accommodate these issues (e.g. multiple endmember mixture modeling), but there remain significant challenges.

**Spectral Modeling:** This is the most physically based approach, where all the aspects of the materials are defined (optical constants, particle size, particle texture, scattering functions, etc.) and the spectra predicted on the basis of radiative transfer models. Similarly this could be run in reverse where these parameters are derived from reflectance through inverse models of radiative transfer. When applied correctly, these models are robust and informative, and they have been verified in some laboratory studies. However, they are not widely applied to remotely acquired data due a number of factors (complexity, lack of input information, lack of sufficient observations to constrain parameters, etc.).

**Conclusions:** Among the approaches outlined here there are no definitive boundaries between these methods, and there is overlap in the type of information and the level of quantification provided. Most investigations take advantage of multiple approaches to achieve their goals, and all have been applied in one form or another to Mars data. However, all approaches are not appropriate for all data. Some important items to consider for future missions:

- Spectral analyses methods should be based on physical principles.
- Methods should be verified or validated with laboratory data or well documented field sites.
- Some methods have been developed on the basis of remotely acquired data where the conditions have not been simulated in the laboratory. Their principles and validation should be validated with laboratory or field studies.

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## MID-INFRARED REFLECTANCE SPECTROSCOPY: WHERE ARE WE, WHERE ARE WE GOING, AND WHY?

Carlé M. Pieters, Brown University, Dept. of Geological Sciences, Providence, RI 02912. Pieters@mare.geo.brown.edu

**Introduction:** Spectroscopic data obtained in the laboratory for known materials provide the foundation for interpretations of remotely acquired spectra. High quality laboratory data are *required* for accurate interpretations but do not guarantee them. Nature presents two problems: 1) If a laboratory spectrum (or its modeled derivative) is shown to “match” that of an unknown surface within acceptable errors, one must independently show that the solution is unique. Unique solutions are rare. 2) Conversely, if one knows the detailed composition of a natural material (say a CI meteorite), it is most difficult to create a spectrally comparable analogue from individual components. In other words, it is hard to fully mimic natural processes.

That said, the goal of most laboratory spectroscopic measurement programs is to document and understand the diagnostic properties of materials and the processes that have acted on them. The map of cause and effect for spectral properties is infinite in n-dimensions and individual researchers must choose to limit the number of variables under study. Principles must normally be generalized from limited data. Ideally, scientific applications drive the type of measurements made, with understanding the physics of the interaction a result.

Examples of mid-infrared laboratory measurements are provided here. Both the type of radiation in the natural environment (reflected or emitted) and the processes involved in absorption (electronic, molecular) vary with wavelength. For the inner solar system, remotely measured radiation beyond  $\sim 7\mu\text{m}$  is essentially thermal emission in origin. Laboratory measurements, on the other hand, have flexibility in configuration and include emission, reflection ( $1 - E$  by Kirchhoff's law), and transmission options, the latter two including *micro*-spectroscopy. This overview is not meant to be complete nor provide adequate references, but is intended to stimulate discussion.

**Measurement configurations.** Spectra for olivine samples of different particle sizes are shown in Figure 1 as measured in different laboratories using typical laboratory configurations (spectra discussed in Mustard and Hays, 1997). Features originate from the uppermost surface of particles (surface scattering). Each measurement approach has its strengths and weaknesses (to be discussed), but all spectra exhibit the same fundamental properties: a) prominent Reststrahlen bands for large particle sizes, b) a decrease in strength of the Reststrahlen band with decreasing particle size, coupled with modest variation of shape, c) prominent “transparency feature” for fine particles near  $13\mu\text{m}$

(Salisbury, 1993) which varies regularly with particle size. For comparison, a TES library emission spectrum of a similar olivine with large particle size is shown.

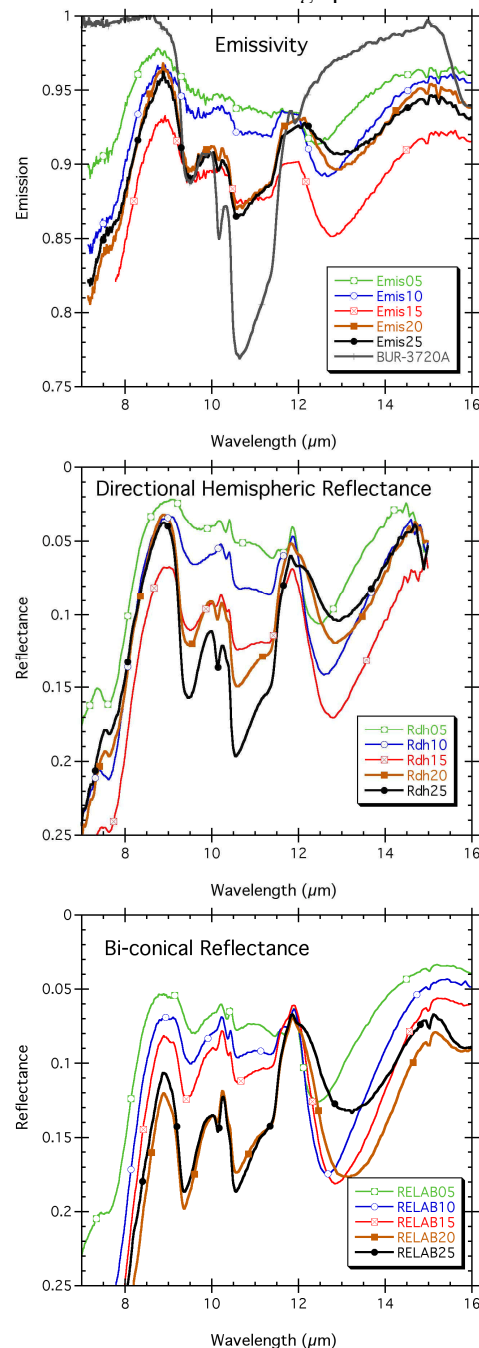


Figure 1. Spectra of particulate samples of olivine (<5, 5-10, 10-15, 15-20, 20-25  $\mu\text{m}$ ) measured with different optical arrangements (after Mustard and Hays, 1997). [Reflectance is shown inverted for comparison with Emission.]

At shorter wavelengths, radiation is largely, if not wholly, reflected solar radiation. Bidirectional reflectance



## MID-INFRARED REFLECTANCE SPECTROSCOPY C. M. Pieters

tance spectra are shown in Figure 2 for the same particulate olivine samples of Figure 1. The features in this part of the spectrum originate from light that has been transmitted through particles before being scattered (referred to as volume scattering).

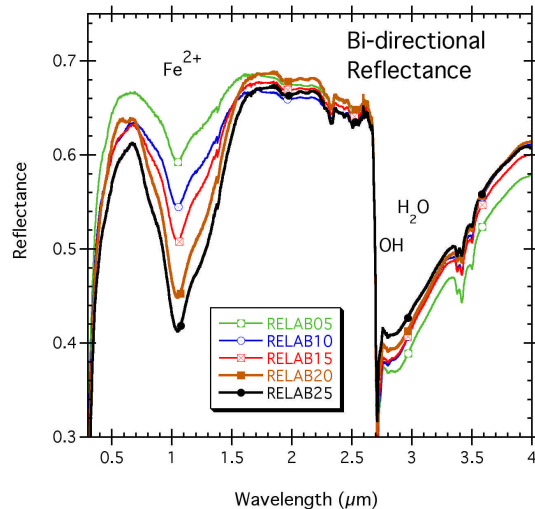


Figure 2. Vis-NearIR Bidirectional Reflectance spectra for the same particulate olivine samples of Figure 1. The weak feature at 2.3  $\mu\text{m}$  is an indication of the small amount of serpentine contamination of the sample.

A second example of comparative measurements is shown in Figure 3. In this case, the Restrahlen bands, prominent in the solid surfaces, almost disappear in the fine fraction. On the other hand, weaker features become apparent at shorter wavelengths where volume scattering is possible with the fine particles.

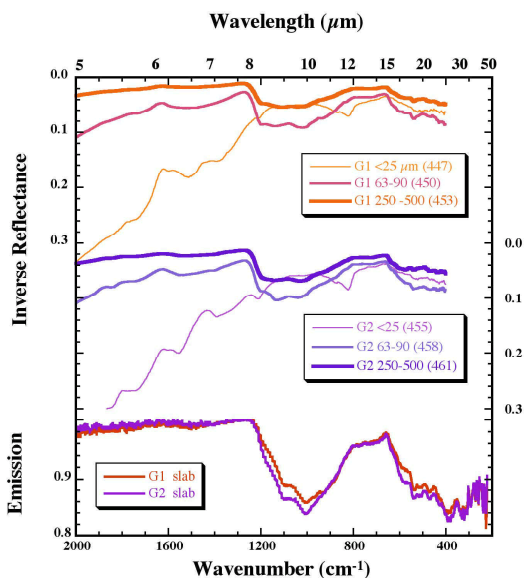


Figure 3. Spectra of two different basalts (G1 and G2) measured both as particulate samples (reflectance) and as slabs (emission) [after Bishop et al., 2002].

**Physical and compositional properties.** The above examples illustrate only a few of the many parameters that are important in building a base of laboratory spectroscopic measurements. Key physical properties include:

- particle size and size *distribution*
- grain size and size *distribution*
- porosity and packing
- environmental conditions (P, T, etc.)

On the other hand, perhaps the most essential information for remote measurements focuses on compositional properties:

- pure minerals
- mineral compositions, including hydration
- mineral mixtures
- alteration and weathering products
- natural rock types

Both forward and reverse measurements are essential. That is, spectroscopic experiments are needed that control the variables and examine the results (forward) as well as studies that examine natural materials and document their properties and range of variables (reverse). The challenge is to have the two converge.

Examples of initial measurements for almost all the above now exist, at least to the extent of documenting their importance. Nevertheless, even the most well intentioned “library” of spectra is incomplete.

**Modeling and Applications.** Spectra for each of the above variables (a – i) are affected by the other variables. The number of possible experimental dimensions is huge, reflecting the diversity of natural surfaces and processes that act on them. Modeling approaches, both empirical and physical, are essential to bridge the gaps between experimental laboratory measurements and to make predictions for comparison with the natural environment. The critical and cyclical cornerstones that support successful remote compositional analyses are thus: laboratory – model – application – laboratory – model – etc.

So, *why* do any of this? Because understanding the mineralogy of a surface is central to understanding the character and geologic evolution of a planetary body on the local, regional, and global scale. Because spectroscopic techniques provide powerful remote compositional analysis tools. And because our understanding of how radiation interacts with natural materials is inadequate. We have much to learn and much to explore.

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**USING TERRESTRIAL MULTISPECTRAL IMAGES AS A PROXY FOR CONSTRAINING NEW THERMAL INFRARED DATA OF MARS.** Michael S. Ramsey, *Department of Geology and Planetary Science, University of Pittsburgh, Pittsburgh, PA, 15260-3332, ramsey@ivis.eps.pitt.edu*

**Introduction:** The physical and erosional environments on Earth and Mars are clearly very different. Hyperspectral TIR data returned from the Thermal Emission Spectrometer (TES) instrument thus far has revealed only a few minerals [1,2]. However, with a thirty-fold increase in spatial resolution, the Thermal Emission Imaging System (THEMIS) instrument offers the potential of mapping very small regions. The author has shown that distinct minerals comprising only 5-10% of a spectrum (or pixel) can be identified using linear deconvolution [3]. This means that objects as small as 500–1000 m<sup>2</sup> are potentially detectable, leading to possibility of identifying minerals within ejecta blocks, sand dunes, and crater walls. However, these positive mineral identifications will be hindered by the multispectral resolution of THEMIS coupled with the complicating factors of the Martian atmosphere and surface dust deposits.

Contrary to common perceptions, these factors are not enough to cause failure in extraction of mineral end-members on the surface. Much of the accuracy and confidence in such an approach relies on precursor field and laboratory investigations using terrestrial orbital instruments such as the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER), which compare favorably to the THEMIS spectral and spatial resolutions (Table 1). In addition to field-based calibration/validation efforts using these data sets, a robust search algorithm will be necessary in order to winnow mineral libraries for the best-fitting end-member spectra.

**Background:** Multispectral TIR data sets have been the primary research tool of the author for over ten years, focusing on planetary analog sites such as dune fields, volcanic lava flows, and impact craters [4,5,6]. These studies have confirmed the need for detailed field and laboratory-based research in order to validate unit identification algorithms operating on low spectral resolution data. For the first time, a similar data set will be available for the Martian surface. The THEMIS instrument has begun to return multispectral TIR data from Mars at a relatively high spatial resolution (100m/pixel). There now exists TIR data that is both high spectral/low spatial resolution (TES) and high spatial/low spectral resolution (THEMIS). Under the appropriate conditions and with new mapping tools under development, small-scale (<2 km) and potentially very recent geomorphic features such as meteorite impact craters can be examined. An important deficit in the current TIR mapping approach at Mars is a methodology for quantitative extraction of mineralogy with scale-dependant modeling of data using

proxy sites on Earth. By analyzing actual orbital data from impact craters and dune fields, combined with field mapping and new mineral identification approaches, a detailed framework for THEMIS data returned from similarly-preserved, though much older, units on Mars can be constructed.

**Deconvolution Model:** The fundamental goal of remote sensing measurements, whether in the laboratory or from space, is to determine the physical and chemical characteristics of the object under study. One technique employed to ascertain the surface mineralogy is spectral deconvolution, which has been used for a variety of scientific problems involving mixture analyses [2,3,4,7,9]. Deconvolution provides a relatively straightforward and computationally quick method of assessing the mineral assemblages of a surface, thereby reducing the data set to a minimum informational volume. In general, linear deconvolution has been extensively modeled and tested in the laboratory, at terrestrial analogs, and on Mars surfaces using current TES data with much success by numerous authors [2,3,8,9]. However, the limitations of such an approach are driven by the spatial and spectral resolution of the data, as well as the breadth of the available spectral library.

The over-arching principle of linear mixing is the spectral features of the end-member minerals overlap and combine to form a composite spectrum in linear proportion to their areal fractions. The residual error, expressed as a single value for the entire wavelength region, is known as the root-mean-squared (RMS) error and determines the “goodness of fit” for a particular model iteration. This value can be used as an indicator of the appropriateness of the chosen end-member suite.

This methodology is constrained by several assumptions in order to provide meaningful results. Foremost, the approach allows a maximum number of end-members equal to one plus the total number of equations or instrument wavelengths. This becomes a critical limitation in attempting to deconvolve multispectral data using large spectral end-member libraries [2,4]. What is currently lacking is a logical approach that winnows large spectral libraries into subsets in order to model the best fitting combination of minerals.

**Automated Blind End-Member Analysis:** Such an approach, known as blind end-member analysis, can be automated and used to refine an iterative solution to linear deconvolution of THEMIS data using hyperspectral mineral libraries [10]. A methodology such as this is critical if the multispectral THEMIS

## CONSTRAINTS ON THE ANALYSES OF MARTIAN TIR DATA: M.S. Ramsey

data are to be interpreted for quantitative model mineralogy of the Martian surface. Thus far, hyperspectral TES spectra have been commonly deconvolved using two or three surface end-members and two atmospheric end-members [1,2]. The use of a large suite of unknown end-members, however, provides an assurance that the unknown or mixed spectrum is being tested for all possible mineral combinations. In effect, no constraints are placed on the algorithm and its results can be assumed to be the best possible for fit of the available end-members to the unknown spectrum. For the case where the number of wavelength bands is far less than the number of available end-members, this liberal use of a large data set is impossible. In this case, a strategy must be devised to test all the end-members without violating the fundamental mathematical constraint.

One reason the concept of an automated, blind end-member algorithm is difficult to grasp is the sheer quantity of calculation involved. For example, using combinatorial mathematic algorithms, the number of possible end-member combinations of 5 or less in a library of 170 spectra is 1,115,034,284 [11]. Despite this large number of iterations, a level of analysis such as this may be required in order to accurately model the surface spectra. What remains to be assessed is the computer processing time required, the accuracy of the results, and the applicability to current terrestrial data sets.

**Study Sites:** Much of the initial model development and testing for this type of data analyses was carried out on Mars surface analogs such as active dune fields, recent impact craters, and ancient volcanic terrains [4,5,6]. The only study using a blind end-member approach was carried out at the Kelso Dune Field in the Mojave Desert, CA [4]. The results of this study confirmed the applicability of such an approach. The correct suite of end-members was chosen in over 94% of the pixels, and the values of the derived surface percentage compared very well with values derived from petrographic techniques. This study and recent work at

Meteor Crater, AZ indicate that development of computationally-optimized, permutation-based code that iterates the deconvolution software through the entire spectral library is critical for the success of THEMIS data analyses [6].

**Conclusions:** Continued work on these data sets and field areas will provide insights into fundamental areas of Mars surface mineralogy and geologic processes. The overall objectives are highly relevant to the goals of both the THEMIS instrument as well as the those of the Mars 2001 project, in particular and the Mars Exploration Program in general. For example, of the four specific science objectives proposed by the THEMIS instrument, three are addressed in this study:

- i. to determine the mineralogy and petrology of localized deposits ...
- ii. to provide a direct link to the global hyperspectral mineral mapping from the MGS TES ...
- iii. to study small-scale geologic processes and landing site characteristics ...

In addition, several of the Mars 2001 mission science objectives are also met:

- i. globally map the elemental composition of the surface ...
- ii. acquire high spatial and spectral resolution images of the surface mineralogy ...
- iii. provide information on the morphology of the Martian surface ...

**References:** [1] Bandfield, et al., *Science* 287, 1626-1630, 2000. [2] Christensen, et al., *JGR* 105, 9609-9621, 2000. [3] Ramsey and Christensen, *JGR* 103, 577-596, 1998. [4] Ramsey, et al., *GSA Bull.* 111, 646-662, 1999. [5] Ramsey and Fink, *Bull. Volc.* 61, 32-39, 1999. [6] Ramsey, *JGR (in press)*, 2002. [7] Adams, et al., *JGR* 91, 8098-8112, 1986. [8] Thomson and Salisbury, *RSE* 45, 1-13, 1993. [9] Hamilton and Christensen, *JGR* 105, 9717-9733, 2000. [10] Christensen et al., *JGR* 105, 9735-9739, 2000. [11] Kreher and Stinson, *CRC Press*, 1999

Table 1. ASTER and THEMIS design specifications

	ASTER	THEMIS
Wavelength Range ( <i>VIS-SWIR</i> ) [ $\mu\text{m}$ ]	0.58 - 2.43	0.45 - 0.75
Wavelength Range ( <i>TIR</i> ) [ $\mu\text{m}$ ]	8.13 - 11.65	6.5 - 14.5
Spectral Resolution( <i>VIS-SWIR</i> ) [bands]	9	5
Spectral Resolution ( <i>TIR</i> ) [bands]	5	9
Spatial Resolution( <i>VIS-SWIR</i> ) [m]	15, 30	20
Spatial Resolution ( <i>TIR</i> ) [m]	90	100

## SCIENCE INVOLVEMENT IN MARS EXPLORATION IN THE FIRST DECADE OF THE TWENTY-FIRST CENTURY. R.S. Saunders, NASA, JPL

The Mars Exploration Program is a long-term program initiated by NASA. The scientific objectives of this program are to: (1) Search for evidence of past or present life, (2) understand the climate and volatile history of Mars, (3) determine the evolution of the surface and interior of Mars, and (4) prepare for human exploration. The planned missions beyond the 2005 opportunity will be designed to be responsive to scientific discoveries in defining their specific objectives. The guiding objective of the program is to understand whether Mars was, is, or can be, a habitable world. To find out, we need to fully characterize the planet and understand how geologic, climatic, and other processes have worked to shape Mars and its environment over time. This paper will discuss how current and planned missions support the program objectives and lay out some priorities for observations and supporting research during this decade.

Among our discoveries about Mars, the possible presence of liquid water either in the ancient past or preserved in the subsurface today, stands out above all others. Water is critical to life; water has altered the face of Mars in the past; and water is essential for future exploration. Thus, the common thread of the Mars exploration objectives is to understand water on Mars. The Program seeks to identify past and present sources and sinks; interaction and exchange between subsurface, surface, and atmospheric

reservoirs; and the evolution of the volatile composition over time. The focus of the 2001 element of the Mars Exploration Program, Odyssey, is to map the elemental and mineralogical composition of the surface via orbiter instruments using IR imaging, neutron and gamma-ray spectrometry.

Mars Exploration Rovers in 2003 will land at two sites and examine the detailed mineralogy of rocks and soils with IR imaging. Mars Reconnaissance Orbiter will continue the detailed mineralogical observations with high resolution VIS and multispectral mapping in the visible. Later in the decade, a large capable lander will continue detailed study at a site that is deemed to be the most promising for furthering program objectives. PI conceived and led Scout missions and New Frontiers missions to Mars are expected to play an important role just as the Discovery missions have been vital for Solar System exploration in general. The entire planetary science community, including instrument and mission PIs, laboratory researchers, theoretical and numerical modelers, analog and field researchers and data analyzers all have important roles in the program and must communicate their ideas and new findings to guide the program direction. This new Mars program, far more than in the past, will be developed, owned and operated by the planetary science community.

**DISCRIMINATION BETWEEN SOLID, LIQUID AND GASEOUS H<sub>2</sub>O, AND ASSESSMENT OF H<sub>2</sub>O TEMPERATURE BY SPECTROSCOPY USING THE OMEGA IMAGING SPECTROMETER (MARS EXPRESS).** Bernard SCHMITT<sup>1</sup>, Sylvain DOUTÉ<sup>1</sup>, Stéphane ERARD<sup>2</sup>, Yves LANGEVIN<sup>2</sup>, Jean-Pierre BIBRING<sup>2</sup>. <sup>1</sup>Laboratoire de Planétologie de Grenoble, CNRS - Université J. Fourier, France; <sup>2</sup>Institut d'Astrophysique Spatiale, CNRS - Université Paris-Sud, Orsay, France.

The OMEGA imaging spectrometer (PI: J-P. Bibring, IAS) of the European Mars Express mission will map in the visible and near-infrared (0.5–5.2  $\mu\text{m}$ ) various mineral and volatile species at the surface of Mars during one or two Martian years. In particular OMEGA should be able to: 1) discriminate between the different phases of H<sub>2</sub>O: ice, liquid, gas, mixed with CO<sub>2</sub>, adsorbed, hydration,... 2) map their spatial distribution and 3) monitor their diurnal and seasonal changes. This may thus provide very useful information about the water cycle on Mars and its relationship with the atmosphere, surface and aerosols.

In this talk we will first present the optical constants of H<sub>2</sub>O ice and liquid water recorded in the near-infrared as a function of temperature (Grundy and Schmitt 1998, Schmitt et al. 1998). Then, using a radiative transfer model in layered surfaces (Douté and Schmitt 1998) we will show how the various phases of H<sub>2</sub>O (ice, liquid, gas, diluted in CO<sub>2</sub> ice) mixed with CO<sub>2</sub> ice or minerals could be discriminated with OMEGA. For that purpose we will consider different coexistence modes of the previous compounds: intimate mixtures, stratification, etc.

Finally we will assess the capability of OMEGA to determine the temperature of H<sub>2</sub>O ice using the temperature dependent behavior of several of its absorption features (Grundy and Schmitt 1998, Grundy et al. 1999). This capability should be of great interest, especially for surface temperature below 180K, below which OMEGA is not sensitive to thermal emission. As a result, temperature maps of the polar caps will be obtained throughout the year (except winter). Additionally, analysis of the OMEGA data should lead to the temperature of cold ice patches mixed under the pixel scale with hotter minerals dominating thermal emission.

**References:** DOUTÉ, S., and B. SCHMITT 1998. A multi-layer bidirectional reflectance model for the analysis of planetary surface hyperspectral images at visible and near infrared wavelengths. *J. Geophys. Res. E*, **103**, 31,367–31,390. GRUNDY, W., and B. SCHMITT 1998. The temperature-dependent near-infrared absorption spectrum of hexagonal H<sub>2</sub>O ice. *J. Geophys. Res. E*, **103**, 25809–25822. GRUNDY, W.M., M.W. BUIE, J.A. STANSBERRY, J.R. SPENCER and B. SCHMITT 1999. Near-infrared spectra of icy outer solar system surfaces: Remote determination of H<sub>2</sub>O ice temperatures. *Icarus*, **142**, 536–549. SCHMITT, B., E. QUIRICO, F. TROTTA, and W. GRUNDY 1998. Optical properties of ices from UV to infrared. In *Solar System Ices*, (B. Schmitt, C. de Bergh, and M. Festou eds.) Kluwer Academic Publ., Dordrecht, Astrophys. *Space Sci. Lib.*, Vol. **227**, pp. 199–240.

## QUANTIFICATION OF NEAR-INFRARED PHOTOGRAPHY OF SNOW SURFACES ON EARTH AND MARS.

Martin Schneebeli, Margret Matzl, Walter J. Ammann, Swiss Federal Institute for Snow and Avalanche Research SLF, CH-7260 Davos, Switzerland

The reflectivity of snow is very high and insensitive to textural properties in the visible spectral band, but sensitive to structural properties in the near-infrared spectral band from about 850-1050 nm. This property has been known for about 20 years (Dozier et al, 1982) and is used to classify snow types in remote sensing. The structural properties of snow are summarized in the grain size, a property which lacks a clear physical meaning in snow. Snow is usually not a granular material, but a sintered material with a large ratio between the shortest and longest diameter and a variety of shapes. We used near-infrared (NIR) photography to document the complex surface of wind-blown snow. In contrast to photography in the visible spectral band, a high-contrast is achieved even at a relatively high sun angle.

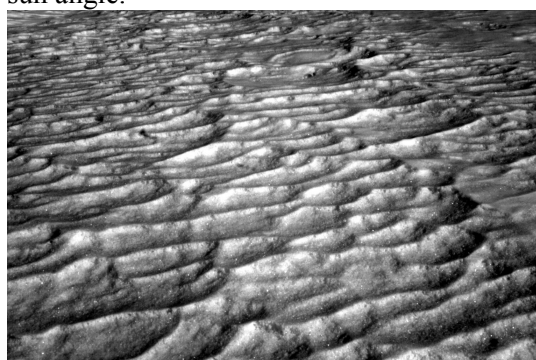


Fig. 1: Surface of windblown snow. Small changes in grain size increase the contrast, giving the image a "sandy" appearance

We used the same method to image snow profiles. We determined on well-documented snow samples the reflectivity and correlated this to structural properties. Different snow structures show at the same "grain size" a slightly different reflection. Grain size was measured as the mean diameter of the grains (without considering a specific orientation). The resulting correlation was used to classify the snow profile images (Fig. 2). This classification was usually superior to the grain sizes determined by the observer especially in detecting and classifying thin layers. Several depositional features not visible to the naked eye

and rarely documented could be routinely detected: cross-bedding, buried sastrugi or disturbed snow layers. With this relatively simple instrument it is now possible to uncover the processes active during the sedimentation of the snowcover at much greater detail than before. In addition, we have a simple tool to objectively document a snow-profile.

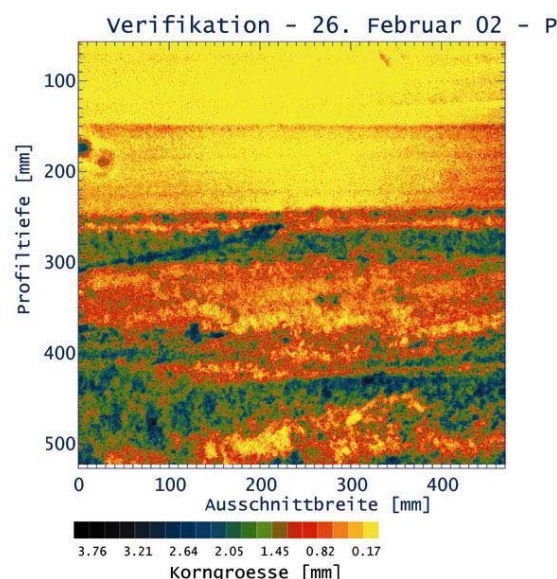


Fig. 2 Snow profile photography in the near infrared-range. The cross-bedding in the middle layer is well visible. The first interface in the top layer was not noticed by the observer.

We believe that by using several spectral bands in the near infrared-range a more detailed analysis of the snowcover properties will be possible than it is with our camera with a peak sensitivity at 890 nm. An instrument like the planned CRISM offers the opportunity, if this instrument could be also applied on terrestrial snow surfaces, to improve our understanding of the complex interaction between reflectivity of snow and its texture. This methodology could then be applied to the understanding of snow metamorphism on Mars. It can be expected that snow metamorphism on Mars will be very pronounced. It might be possible, that different processes than known from Earth snowcover might be dominant.



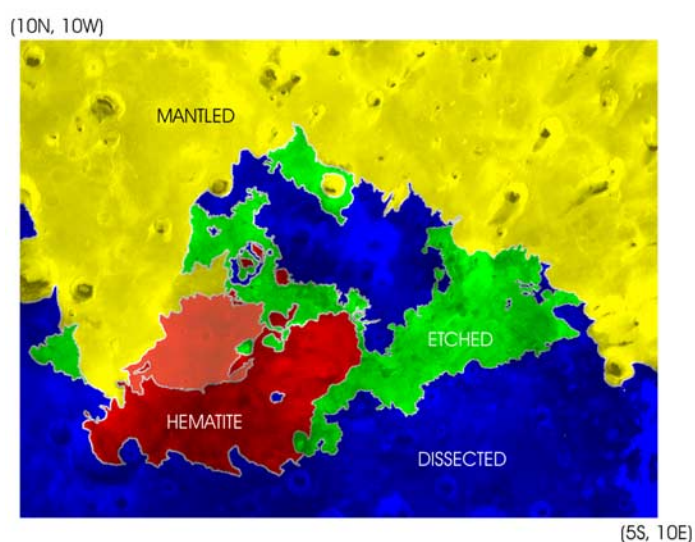
## MANTLED AND EXHUMED TERRAINS IN TERRA MERIDIANI, MARS.

F. P. Seelos IV and R. E. Arvidson, Department of Earth and Planetary Sciences, McDonnell Center for the Space Sciences, Washington University in St. Louis, Box 1169, One Brookings Drive, St. Louis, MO 63130, seelos@wunder.wustl.edu.

Analysis of MOC, MOLA, and TES data from the basaltic hematite-bearing deposits [1] and associated units in the Terra Meridiani region of Mars shows that dissected Noachian-aged cratered terrain was covered by lava flows, cone fields, and ash deposits extending over a lateral distance of approximately one thousand kilometers. We have delineated this volcanic complex and the surrounding area into four units based on remote sensing properties (Figure 1). The hematite-bearing deposits (shown as 'hematite' in Figure 1) represent the top stratum of these volcanic materials, locally reworked into an aeolian lag deposit of basaltic dunes that partially cover a visibly brighter volcanic substrate. The bright substrate is extensively exposed to the north and east of the hematite-rich region ('etched' in Figure 1) and can be discriminated by a high thermal inertia relative to the hematite-bearing unit. The entire volcanic complex is covered in the northern portion of the area by an aeolian sedimentary mantle that is 10's m thick and capped by duricrust ('mantled' in Figure 1). Heavily dissected Noachian terrain is exposed largely to the south ('dissected' in Figure 1). The mantled, etched, and hematite units have been extensively stripped by wind, implying a sequence of deposition and subsequent exhumation.

TES data for these units have been analyzed using the linear deconvolution method [2] (Figure 2) and spectral angle calculations (Figure 3). Despite the fact that the etched material is bright in the visible it has a thermal emission spectrum similar to the dark dissected material to the south. The unusual properties of the hematite-bearing basaltic dunes and the bright substrate can be explained as a consequence of hydrothermal alteration of basaltic glasses and glassy coatings.

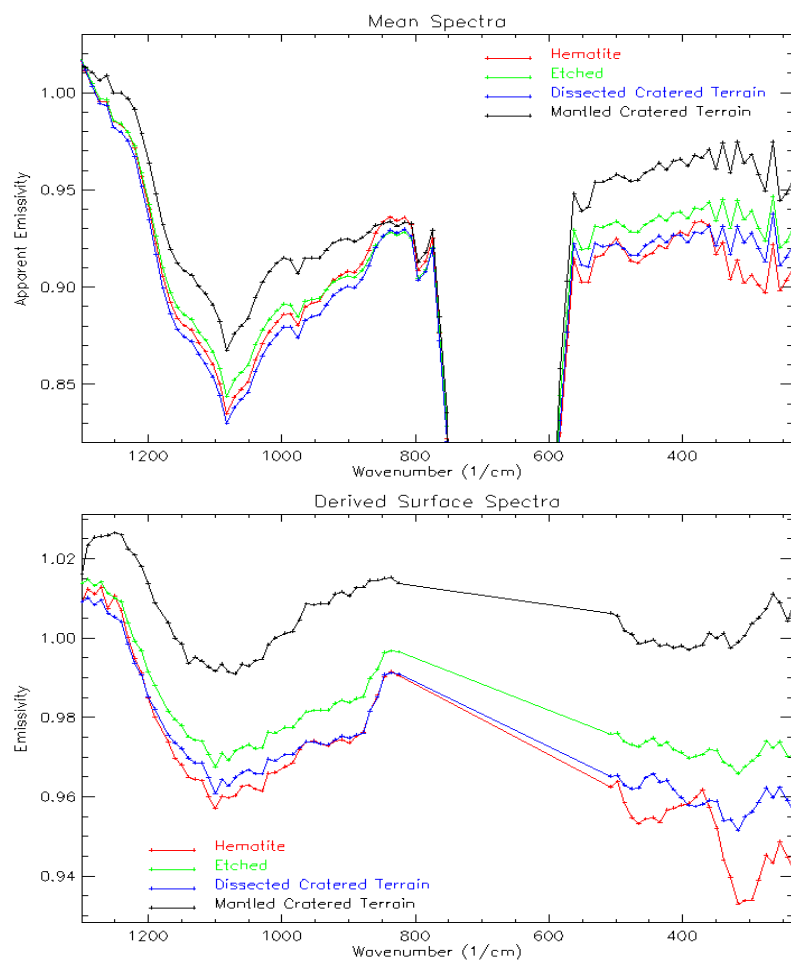
Exploration of the hematite-bearing lag deposits and underlying substrate by the 2003 Mars Exploration Rover will allow testing of the hypotheses presented, including the nature and extent of hydrothermal alteration, since MOC NA data show that the substrate is exposed between the dark dunes on length scales consistent with expected rover traverse distances.



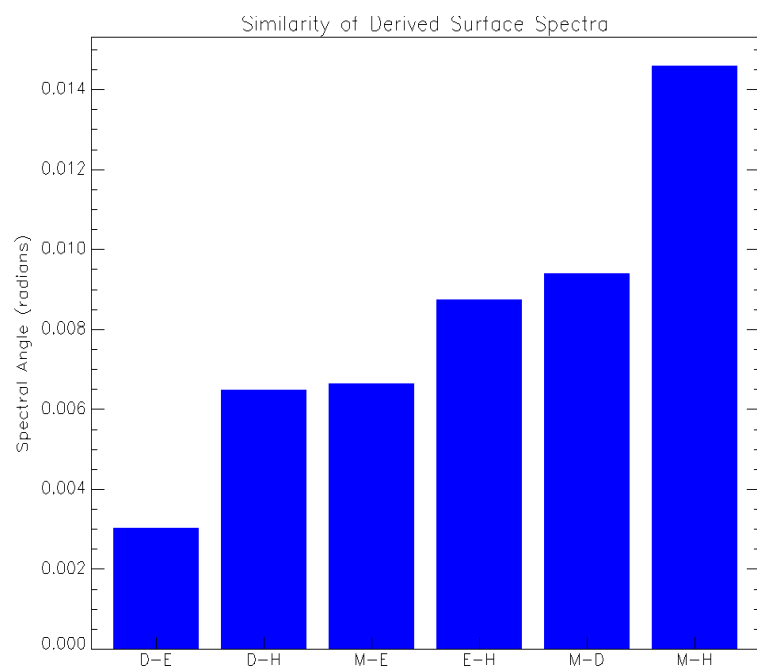
**Figure 1.** Units map for the Terra Meridiani region. After [3], [4].

References: [1] Christensen et al. (2000) *JGR* **105**, 9623-9642. [2] Smith et al. (2000) *JGR* **105**, 9589-9607. [3] Arvidson et al. (submitted). [4] Hynek et al. (submitted).

## TERRAINS IN TERRA MERIDANA: F.P. Seelos et al.



**Figure 2.** Mean apparent emissivity spectra for the four units of interest (top), and the surface emissivity spectra for the same units derived by linear deconvolution (bottom).



**Figure 3.** Spectral angle comparison of the derived surface spectra shown in Figure 1. Smaller values indicate a stronger spectral affinity



**NOVEL IMAGING SPECTROMETER WITH HIGH SIGNAL COLLECTION ABILITY AND NO MOVING PARTS.** R. G. Sellar, L. E. Kirkland, G. D. Boreman and D. Wang

The fundamental difference between spectral studies of Earth and Mars is that terrestrial studies incorporate ground truth, while studies of Mars currently cannot. Thus a terrestrial study may proceed with less information from a spectral data set, since it is augmented by on site information. However, experience gained from spectral studies of Mars, and from Department of Defense studies of the Earth has shown that unambiguous mineralogical interpretations without benefit of ground truth require higher information content spectra than was generally expected. This may explain the lower than expected productivity that has been experienced with infrared studies of Mars. High information content spectra have broad spectral range, high spectral resolution, and high signal to noise ratio (SNR).

A new approach to imaging spectroscopy offers the potential to provide high information content and/or reduce the mass and cost of instruments by combining the principal advantages of two traditional techniques: the signal collection advantage offered by Fourier transform spectrometry (FTS), and the no-moving-parts advantage offered by dispersive spectrometry and filter-array spectrometry. The dramatic advantage in signal collection ability, or *optical responsivity*, would result in several improvements individually or in combination:

- Higher signal-to-noise ratios could be achieved; and,
- A required signal-to-noise-ratio (SNR) could be achieved with a smaller aperture, lowering the required mass; and,
- Higher signal would allow exposure times short enough to obviate the requirement for a pointing mirror or a spacecraft pitch maneuver; and,
- Unlike a traditional FTS, no precision scan mechanism is required.

A general comparative analysis of the signal-collection abilities of the various classes of imaging spectrometer will be shown, and results from a laboratory demonstration of the new technique will be presented.